# A Framework for Space Systems Architecting under Stakeholder Objectives Ambiguity



by

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Submitted to the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Aeronautics and Astronautics

## Abstract

Matching high ambitions with scarce resources is one of the primary challenges of the aerospace industry, on par with the technical challenges of developing new technology. The challenge is further complicated in space exploration, by its own nature aimed at exploring the unknown. Stakeholder objectives are often unclear due to business cases highly exploratory in nature. Further ambiguity emerges from disagreement between stakeholders and decision-makers called to formulate scientific, technological and policy requirements for new systems.

This thesis develops a structured approach to develop recommendations to system architects concerned with the design of unprecedented large aerospace infrastructures for which objectives are ambiguous or unclear. The approach is composed of three parts.

The first part consists in a novel taxonomy of ambiguity in systems design that classifies ambiguities in reducible and irreducible components. Building on this taxonomy, the second part of this thesis develops a Descriptive Systems Architecting Management Framework (SA-MF) to distill canonical forms of ambiguity management from the literature in political science, finance and economics, management, and engineering design. The third part of the dissertation presents a Delphi-Based Systems Architecting Framework (DB-SAF). DB-SAF objectives are to identify sources of ambiguity in the value delivery and tradespace exploration processes, characterize and model sources of ambiguity, mitigate ambiguities through effective systems architecting strategies, integrate the analysis of upstream and downstream architecting processes, and to assess the impact of requirement ambiguities on the architectural tradespace.

The proposed systems architecting approach has been applied to three case studies: the assessment of a robotic Mars Sample Return Campaign, the study of in-space transportation infrastructure for future human space exploration beyond Low Earth Orbit, and the retrospective analysis of satellite constellations for commercial applications. The application of the proposed approach to three different disciplinary fields demonstrates its broad applicability for architecting complex aerospace systems.

This dissertation integrates methods from systems engineering, systems architecting, multivariate statistical analysis, uncertainty modeling, economics, management science and social science research. It allows decision-makers to visualize an architectural synthesis of aerospace systems, understanding adverse impacts of ambiguity, and supporting negotiations among stakeholders for efficient compromise in systems architecting.

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It is true that an education from MIT is like drinking water from a fire hose. I am lucky life and God gave me a chance to spend four years at the Institute and be a Ph.D. student at MIT. I am grateful to the people who made this possible. You have made me a gift for life with your support, affection, and love.

If I had to give the first reason of why a PhD was worth the trouble, is that I met Almudena. On the contrary of what this thesis claims, there is no ambiguity in that she is my main stakeholder! She gives meaning to my days and I love her so much. She gives me unconditional love, support, and happiness. Although being little compared to what she does for me everyday, I dedicate this PhD thesis to her for being the best girlfriend I could ever have. I wish this to be a beautiful start of our future together!

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Ed Crawley is the living definition of the fearless leader. He made a blind bet on me supporting me from day one and making my life at MIT a challenging one. He made my lifelong dream of a NASA summer internship experience come true. He made me travel the world going for conferences in Italy, Switzerland, the US, and South Africa. We went soaring, sailing (sorry for my sea sickness!), golfing and had wine in his Vermont house. In four years I saw him working as MIT professor, being a board member in a rocket company, changing NASA's future as a Presidential Committee Member, opening successful start-up companies in incredibly diverse fields, becoming President of a Russian university and earning his second honorary doctorate degree getting to three PhDs total. Beat that! In the same time period, he also found time to double check my rocket calculation numbers to the last significant digit and pushing me to be better very single day. Thanks for all, Ed. I am so glad and lucky I had such a cool PhD advisor. You once told me 1/4 of your students work for NASA, 1/4 become professors, 1/4 become entrepreneurs, and 1/4 do all of it like you. I hope to be in the fourth bin! Kathi Brazil and Amy Shea gave me invaluable support to find time for me to work with Ed, and provided help for all I needed during my years here. Thank you!!

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Education was a long journey that lasted 3 degrees and 9 years. This thesis is a closure to this chapter of life and brings me to the door of the challenges of the real world.

My goal to influence the course of space exploration starts now!

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# Chapter 1 : Introduction

*Fac ergo, mi Lucili, quod facere te scribis,*
*omnes horas complectere;*
*sic fiet ut minus ex crastino pendeas,*
*si hodierno manum inieceris.*
*Lucius Annaeus Seneca*
*Epistolae ad Lucilium*

## 1.1. Overview

Matching high ambitions with scarce resources is one of the primary challenges of the aerospace industry in the XXI century, on par with the technical challenges of developing new technology. The challenge is additionally complicated in space exploration, which by its own nature is aimed at exploring the unknown. While it is often the case that space missions require large capital expenditures, setting objectives for space exploration is not trivial. Objectives are often unclear due to the ambiguity surrounding the subject of the investigation, which is highly exploratory in its own nature. Ambiguity further arises from disagreement that is often found between experts called to specify science and engineering requirements for missions. Exploration requires large capital expenditures, and therefore becomes problematic in times of tight budget and in presence of several entities seeking to compete for scarce resources to fund their missions.

The history of Human Spaceflight and Planetary Science provide several examples of missions that were cancelled due to budget constraints or disagreement among stakeholders. The outlook for new mission proposals leaves no room for missions not keeping cost in high consideration, while ensuring that objectives are carefully selected and properly reflected into system requirements. Oversights in over-designing requirements, such as setting an excessive mass amount of samples to be returned to Earth, can be fatal to mission success. Over-design increases the overall dry mass of a mission and the number of required development projects. This potentially leads to failure in meeting cost caps. On the contrary, under-designed requirements preclude scientific discoveries and overall value delivery of the mission to stakeholders. In the worst case, poorly specified requirements can lead to not answering any scientific question at all. It is therefore crucial to find the "right answer" (or better, the set of efficient "right answers"), and identify architectures with the highest likelihood of satisfying goals, finding consensus among stakeholders, while meeting engineering and programmatic constraints.

This thesis presents a systems architecting framework aimed to define, identify, characterize, mitigate and analyze ambiguity in the systems architecting process. The framework identifies areas of opportunity of ambiguity mitigation, and develops information of interest to develop recommendations in support of system architects and involved decision-makers. The goal of this work is to support Decision Makers, Program Managers and Principal Investigators in reducing ambiguity in their objectives, identifying architectures with effective and robust programmatic trade-offs, engineering performance, and meet desired science and policy objectives.

This thesis integrates methods from systems engineering, computational systems architecting, multidisciplinary system design and optimization, uncertainty modeling, utility theory and social science research. It allows decision-makers to visualize an architectural synthesis of their engineering systems, understand the impact of ambiguity in the definition of requirements, and consequently support negotiations in reaching consensus towards "*globally best*" system requirements and associated Pareto-efficient system architectures.

## 1.2. Stakeholder Ambiguity in Systems Architecting

As large complex engineering projects involve significant expenditures and span several decades, effective systems architecting is a critical element of the lifecycle process. Systems architecting is the process of transforming a set of needs and goals into an architecture for a system (Simmons 2008). An architecture is the underlying structure and set of relationships of the elements of a system, that forms the basis for engineering design (NASA 2007).

The first threat to successful architecting is posed by unidentified and unmitigated ambiguities in defining what is value and how to maximize value delivered to stakeholders by conceiving, designing and operating complex systems. This section describes the problem of system architecting under ambiguous stakeholder objectives and outlines the goals pursued by the thesis.

Systems are developed to deliver value and satisfy the needs of supporting stakeholders, following a *value delivery process* (Crawley 2008). The OPM diagram (Dori and Crawley 2002) shown in Figure 1 represents the value delivery process for a family of systems.

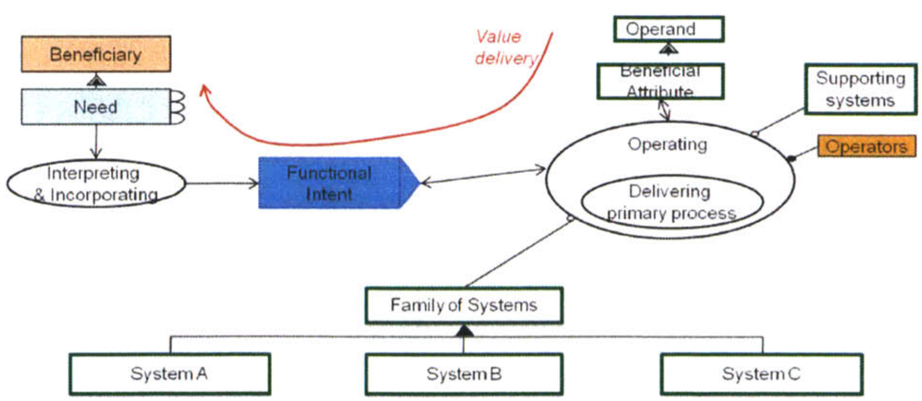



Figure 1 Value delivery process (adapted from (Crawley 2008))

Systems are developed to satisfy a set of needs, elicited by some beneficiaries (or stakeholders). For instance, consider the example of the future US launch infrastructure for human space exploration. In this case, Congress and the aerospace industry are among main stakeholder groups.

System architects interpret and incorporate stakeholder needs into a set of functional requirements. For launch infrastructure, instances of functional requirements are:

*The US launch infrastructure shall be able to:*

1) *Deliver 25mt payloads to a 200 km Low Earth Orbit;*
2) *Deliver 30mt payloads to Escape Orbit;*
3) *Deliver 30mt payloads to a Near Earth Asteroid (4 km/s beyond Escape).*

Once functional requirements are elicited, system architects explore the tradespace of feasible architectures, considering architectural alternatives to identify promising concepts for further study (Ross and Hastings 2005; NASA 2007).

Functions correspond to a set of physical *forms* (in Figure 1, System A, B and C). The architecture in its functional form includes interfaces with intended operators and supporting systems. Forms deliver value by performing intended functions therefore satisfying stakeholders' needs. In the launch infrastructure example, the primary function of the architecture is "delivering payloads to orbits specified by the customer's desired orbital parameters". For given functional requirements, the associated set of forms in this example is the family of launch vehicles designed for intended payloads and target orbits. Figure 2 shows a notional family of launch infrastructure, composed of three vehicles. Vehicle 1 is a vehicle for small payloads to LEO, designed to meet functional requirement 1 in the example above. Vehicle 2 is a heavy lift vehicle designed to meet functional requirement 2, and Vehicle 3 is a super heavy lift vehicle designed to meet functional requirement 3.

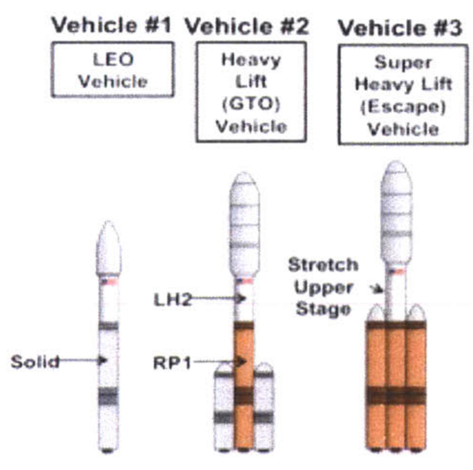



Figure 2 Notional family of launch vehicles (adapted from (Aliakbargolkar and Crawley 2010))

Value delivery of architectures to the stakeholders is affected by uncertainty (de Neufville 2003; Hastings, Weigel et al. 2003; Hastings and McManus 2004; Smaling, de Weck et al. 2004). As Figure 3 shows, there are two segments of the value delivery process where uncertainty occurs, i.e. on the family of systems being designed (uncertainty "*in*" the problem), and on the stakeholder needs (uncertainty "*on*" the problem, or *ambiguity*).

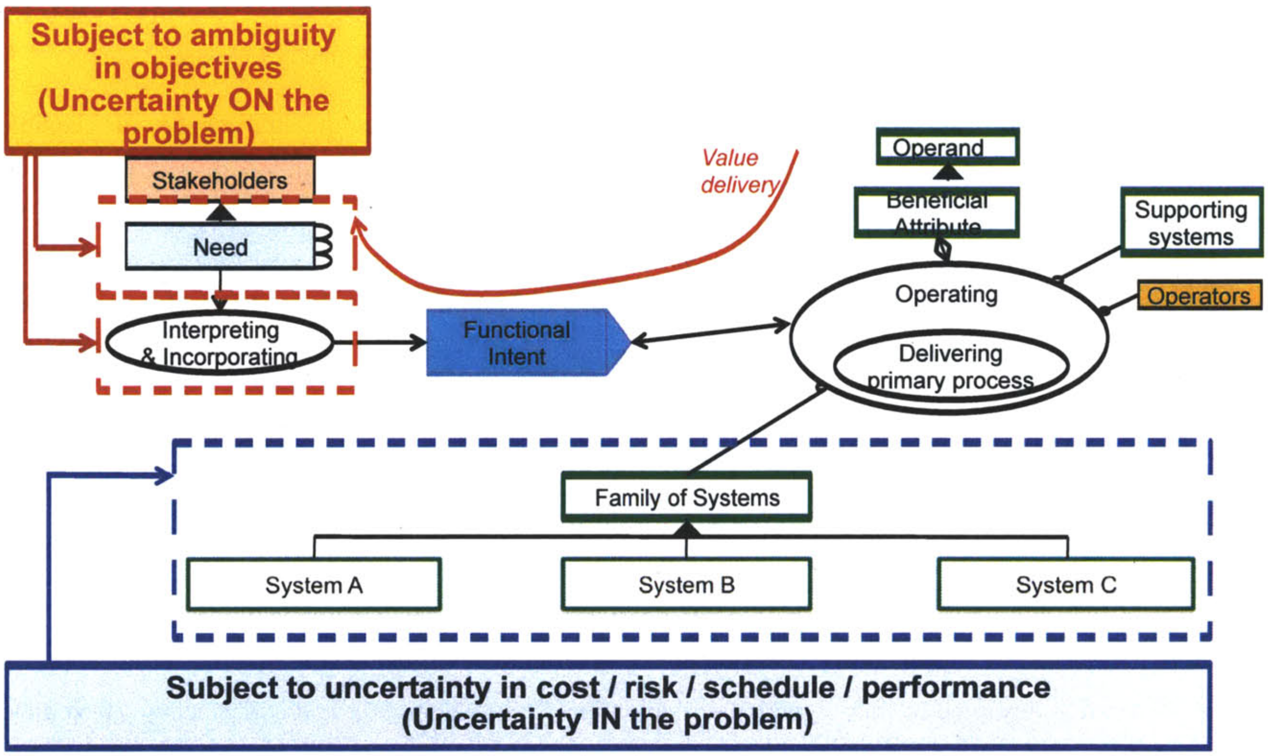



Figure 3 Distinction between processes subject to ambiguity (uncertainty ON the problem) and processes subject to cost / risk / schedule / performance uncertainty (uncertainty IN the problem)

Examples of uncertainty "in" the problem in the launch infrastructure are:

- **Uncertainty in technical performance:** on the stage inert mass fractions, on payload capability for a given target orbit, on the specific impulse delivered by engines, etc.
- **Uncertainty in market demand:** on the number of launches per year per launch vehicle, on the cost to the customer per kg of payload delivered.

The analysis of uncertainty in system design (meant as uncertainty "in" the problem) has been thoroughly explored in the literature, as discussed in the literature review in Chapter 2. The analysis of uncertainty "on" the problem, which is on the ambiguity in stakeholder needs, is a research opportunity that has not yet been explored quantitatively in systems architecting and engineering design. This thesis addresses this gap. Specific research gaps that have been identified are discussed in detail in Section 2.4 following the literature review.

With ambiguity in mind, consider the functional requirements in the launch infrastructure example:

*The US launch infrastructure shall be able to:*

1) *Deliver 25mt payloads to a 200 km Low Earth Orbit;*
2) *Deliver 30mt payloads to Escape Orbit;*
3) *Deliver 30mt payloads to a Near Earth Asteroid (4 km/s beyond Escape).*

Two fundamental assumptions lie behind those requirements, namely on desired payload capabilities and on target destinations. Furthermore, while Low Earth Orbit and Escape Orbit are well defined and bounded in terms of required delta V, Near Earth Asteroids (NEA) are obviously not. Hence, this example shows two categories of uncertainties "on" the architecting problem. From now on, we will always refer to those as "*ambiguities*" to make a clear distinction from traditional uncertainties "in" the problem described previously. The launch infrastructure example shows instances of different classes of ambiguity:

- **Ambiguity in stakeholder needs:**
  - **Ambiguity on launch infrastructure needs:** Are stakeholders going to support the development of three different launch vehicles in a long term development scenario?
  - **Ambiguity on desired payload capability:** Are stakeholders likely to perceive the need of achieving payload capabilities of 25mt to LEO / 30mt to Escape / 30mt to NEA in the long term, or are such capability perceptions subject to change over time? For instance, at the time of writing this thesis the US human spaceflight enterprise is undergoing a time of change in perceived needs. While the previous Constellation program focused on a transportation infrastructure designed to return astronauts on the Moon, the new program under the Obama Administration shifted NASA towards the development of technologies for a mission to a Near Earth Asteroid (Nasa 2010).
  - **Ambiguity on desired destinations:** Are NEAs still going to be the desired first destination for human space exploration of the next three decades? How is the exploration architecture affected by evolving destination requirements and associated change in required transportation capabilities? Is the architecture designed as robust to time evolving stakeholder objectives?
- **Ambiguity in interpreting and incorporating stakeholder needs:** How is the NEA destination for human space exploration going to be selected? Figure 4 shows a cumulative distribution plot of all

known NEAs from a database maintained by NASA JPL (Benner 2011), showing that the 50% percentile of NEAs is at reach within 4km/s beyond Escape orbit with a 30mt payload. The functional requirement for the launch vehicle system in the example above has been stated using these reference numbers for required destination delta V and payload capability. However, the upward tail of the NEA distribution suggests that 50% of possible NEA destinations are <u>not</u> at reach of such launch infrastructure with the same desired payload capability. To date, there are 7,759 possible NEA destinations and required delta V is not the only value-related metric of interest to stakeholders. Other metrics of interest are likely to be considered by a subset of stakeholders, such as NEA composition, available resources on the surface and other physical properties of NEA surfaces of interest to the scientific community (Nolan 2010).

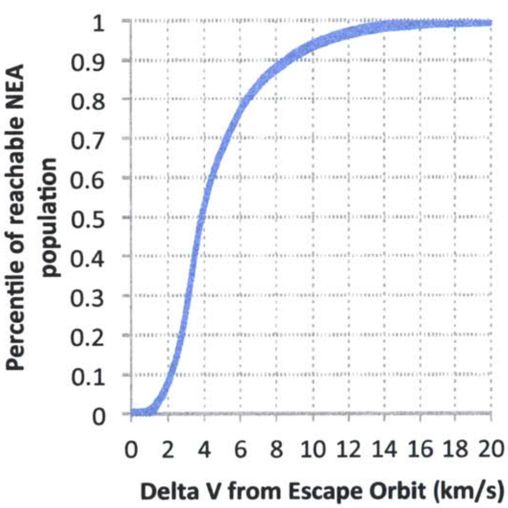



Figure 4 Cumulative distribution plot of delta V required beyond Escape Orbit to reach Near Earth Asteroid destinations (data source: (Benner 2011))

**4 Stage Stack - Serial Burn**

| | |
|---|---|
| *Payload Mass to Baseline NEA (mt)* | 30 |
| *4th Stage (EDS) Propellant Mass (mt)* | 73 |
| *4th Stage (EDS) Dry Mass (mt)* | 8 |
| *4th Stage (EDS) Specific Impulse (s)* | 400 |
| *3rd Stage Propellant Mass (mt)* | 271 |
| *3rd Stage Dry Mass (mt)* | 30 |
| *3rd Stage Specific Impulse (s)* | 400 |
| *2nd Stage Propellant Mass (mt)* | 1003 |
| *2nd Stage Dry Mass (mt)* | 111 |
| *2nd Stage Specific Impulse (s)* | 400 |
| *1st Stage Propellant Mass (mt)* | 3716 |
| *1st Stage Dry Mass (mt)* | 413 |
| *1st Stage Specific Impulse (s)* | 400 |


Figure 5 Notional 4 Stage Launch Vehicle to deliver a 30mt payload to the Baseline NEA (4 km/s beyond Escape Orbit)

Uncertainties "on" the problem are equally relevant as uncertainties "in" the problem traditionally considered by engineers in the system architecting process. In the launch infrastructure example, consider the case shown in Figure 5 where a 4 stage, serial burn launch vehicle is designed to deliver 30mt to a NEA at 4 km/s beyond Escape Orbit (to satisfy functional requirement 3 of our example – from now on referred to as the "*Baseline NEA*" case). For sake of simplicity, the underlying concept of operations is a direct delivery of the payload to the NEA, without any use of on-orbit refueling or convoluted assembly operations. If the launch vehicle is operated at an off-nominal destination delta V - for example because the interest of stakeholders switches to a NEA at 6 km/s beyond Earth Escape orbit instead of the original 4 km/s - then the allowable payload capability decreases drastically. As Figure 7 shows, the selected launch vehicle architecture is unable to deliver any payload to a destination farther than 10 km/s beyond Escape, corresponding to approximately the 92% percentile of the entire NEA population known today (Figure 8). A decreased payload capability corresponds to a degradation of mission objectives, as less equipment can be brought for exploration, and in some cases it corresponds to a total failure of the architecture of accomplishing any goal, when the launch vehicle is unable to deliver critical elements of the in-space transportation architecture such as a manned capsule or a habitat.

This example shows that consideration of ambiguity in stakeholder needs is therefore critical to ensure success in delivering value.

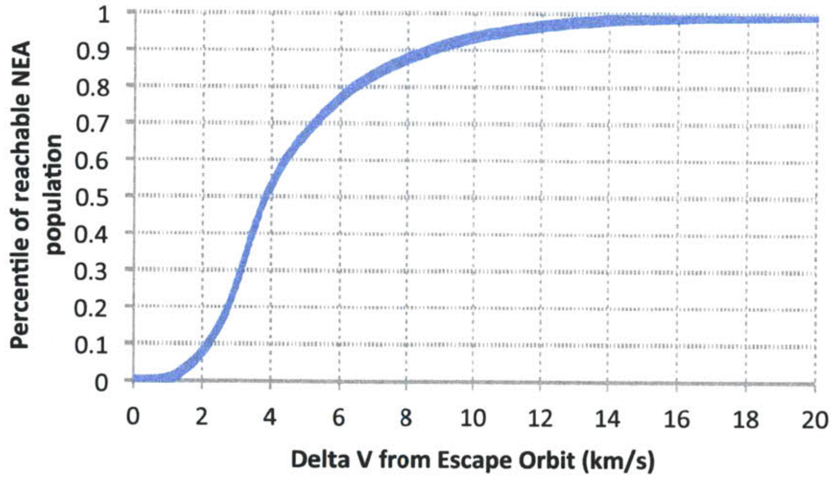



Figure 6 Cumulative distribution plot of delta V required beyond Escape Orbit to reach

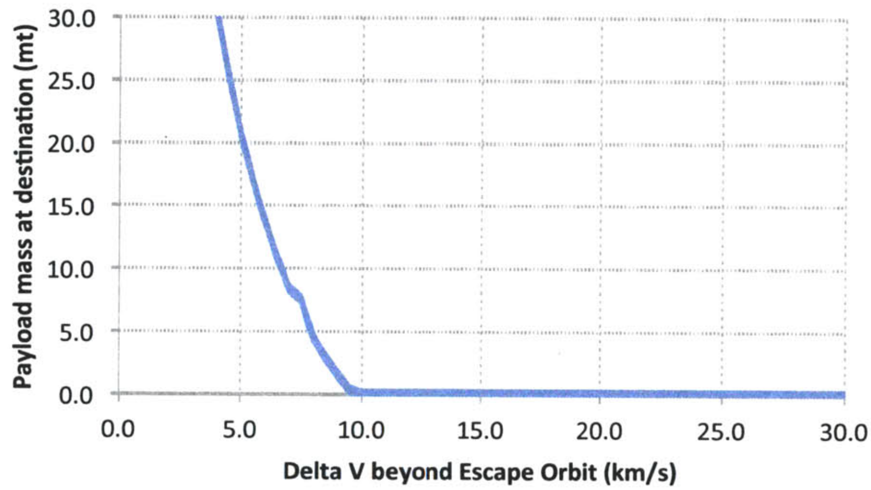



Figure 7 Sensitivity of 4 stage launch vehicle payload mass to destination delta V

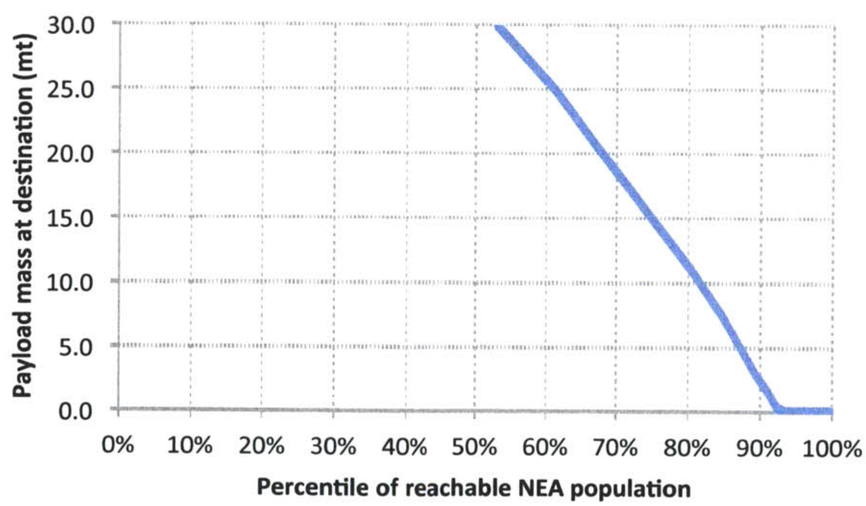



Figure 8 Sensitivity of 4 stage launch vehicle payload mass
to reachable NEA population percentile

Ambiguity in stakeholder objectives deserves careful consideration when the following conditions are met:

- **High degree of innovation in system objectives and stakeholder needs:** the systems being designed are intended to fulfill stakeholder needs with a high degree of innovation, which is the case of early Research & Development ventures, human space exploration, robotic exploration of the Solar System and so forth. The goals of highly innovative research projects are prone to abrupt changes, according to progress made, as soon as new discoveries are made. Breakthrough discoveries could drastically change the focus of the enterprise;
- **Large scale systems translate into large scale failures in worst case scenarios:** the potential impact of ambiguity is greater where systems being architected are large-scale, as they involve the investment of significant resources. This is often the case in the aerospace industry where projects typically range hundreds to billions of dollars.
- **Higher leverage on final outcomes during the early phases of the design process:** system architects have the greatest leverage in the outcome of the project, as they operate in the early phases of the design stage (conceptual design). This is particularly important for architectures which systems are all yet to be developed, such as the architecture of the future human space exploration infrastructure. Figure 9 shows that roughly 70% percent of the total lifecycle cost is typically committed in early architecting stages, and that modification costs increase significantly as the project moves through the lifecycle (INCOSE 2010). Therefore, if critical decisions are made around ambiguous objectives, and ambiguity is not considered as part of the tradespace, the final outcome of the entire venture is put at stake.

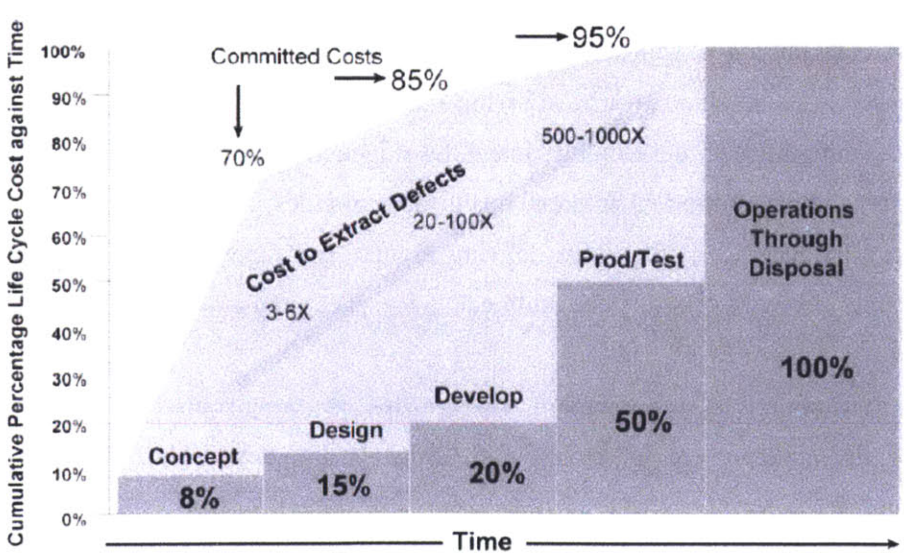



Figure 9 Committed Life-Cycle Cost versus Time (image source:(INCOSE 2010))

- **Large-scale systems have lifecycles spanning several decades, leaving large windows of opportunity for stakeholder objectives to change over time:** while the lifecycle of a large-scale engineering project could several decades, the timescale of policy lies in shorter time spans. An example from the aerospace domain is the Space Shuttle, decommissioned in 2011, which development started in the early 1970s (Jenkins 2001). This is also found to be true in other engineering domains (Miller and Lessard 2000). For instance, in petroleum engineering a typical offshore oil platform design lifecycle is in the order of 30 years (Lin 2008). On the other hand, policy changes happen in shorter arcs of time: a presidential mandate in the United States is of 4 years; therefore a project lasting 30 years will see in the worst case up to 8 potential opportunities of drastic policy changes.

Traditionally, uncertainty in engineering systems is associated with the idea of a threat to the success of a system development (Sage 1995; Kumamoto and Henley 2000; Garber and Pate-Cornell 2004; Weigel and Hastings 2004); however, this view does not account for the upsides opportunities offered by uncertainty. Research in real option analysis and engineering systems design has shown that traditional uncertainty "in" the problem can represent an opportunity for improved system outcomes (de Neufville 2003; McManus and Hastings 2006). This thesis aims at extending this idea to the management of ambiguities in stakeholder objectives, i.e. uncertainties "on" the problem of interest.

## 1.3. Thesis Objectives

This thesis develops a comprehensive quantitative framework aimed at satisfying the following **thesis objectives**:

1) **Identify** sources of ambiguity in the value delivery and tradespace exploration processes;
2) **Characterize** and model sources of ambiguity on the beneficial attributes that contribute to value as delivered to stakeholders, while satisfying stakeholder needs;
3) **Mitigate** ambiguities by developing system development strategies to cut the downside effects of ambiguity while exploiting its potential upside opportunities;
4) **Integrate** the analysis of the value delivery process and functional intent definition (upstream architecting processes) with conventional tradespace exploration (downstream architecting processes).
5) **Assess the impact of requirement ambiguities on the architectural tradespace**, and to improve the achievement of global optimaliity in the down-selection of preferred system architectures;
6) **Develop recommendations** to decision-makers to support decisions on the selection of a system architecture for the enterprise of interest.

## 1.4. Summary and Thesis Outline

The goal of this thesis is to define, identify, characterize, mitigate and analyze the problem of systems architecting under stakeholders ambiguity. The thesis develops a theoretical background and a multidisciplinary framework to explicitly include ambiguity in the definition of the functional intent of a system, and integrate requirements definition of the broader systems architecting. This work aims to support Decision Makers, Program Managers and Principal Investigators in reducing ambiguity in their objectives, identifying architectures with effective and robust programmatic trade-offs, engineering performance, and meet desired science and policy objectives.

The remainder of the thesis is structured as follows. Chapter 2 presents a literature review, to provide intellectual background to the thesis and to support the identification of research gaps being pursued. Based on these premises, Chapter 3 develops an analytic framework to define ambiguity in upstream systems architecting processes, and describes the Comprehensive Approach for Systems Architecting under Ambiguous Stakeholder Objectives. The approach is composed of two parts: a Descriptive Systems Architecting Management Approach, and a Delphi-Based Systems Architecting Framework. Chapter 4 and Chapter 5 present two case studies that have been developed to demonstrate the approach in two applications from the domains of robotic exploration of the Solar System and Human Spaceflight. Namely Chapter 4 presents the architecting case of the Mars Sample Return Campaign, and Chapter 5 presents the architecting case of the in-space transportation infrastructure for future human space exploration beyond Low Earth Orbit. Chapter 6 presents a retrospective case study of the approach, consisting in a pilot study to validate the proposed approach by means of statistical analysis on a systems architecting role play that has been conducted with graduate students from MIT. The thesis closes with Chapter 7, presenting a cross-case analysis that synthesizes the major findings of this thesis and lessons learnt. Research contributions developed in the thesis are discussed in this chapter along with conclusions and the identification of avenues for future research. Chapter 8 lists bibliographical references used in the thesis; Chapter 9 provides appendix material as further documentation of the case studies.

# Chapter 2 : Literature Review and Identification of Research Gaps

Systems architecture and stakeholder ambiguity are highly multidisciplinary topics. A broad literature review is required to gain an understanding of the state of the art in this emerging field and to identify areas of research opportunity. This section presents a review of literature of interest to the problem of architecting systems under ambiguity in stakeholder objectives. The literature review is structured in three parts, leading to the identification of research gaps in Section 2.4.

The first part overviews definitions of uncertainty and ambiguity as discussed in existing taxonomies in the literature. This semantic review is not exhaustive, as uncertainty and ambiguity cover a variety of other fields such as the physical sciences, psychology and other social science research in general. Nevertheless, it provides a comprehensive overview of the themes of interest to this thesis.

The second part is a multidisciplinary survey on tools and methods being employed in science and engineering to cope with uncertainty and ambiguity. The topic is analyzed in a cross-disciplinary fashion, spanning political science, finance, economics, management and engineering. This part of the review analyzes the theme of ambiguity and uncertainty within and beyond engineering systems, identifying intellectual connections of interest.

The third part of the review expands in detail on multidisciplinary themes with direct relevance to the research objectives of this thesis. Table 1 shows the mapping between reviewed themes and thesis objectives. Key literature in the following fields is overviewed:

- **Systems Architecting** (Section 2.3.1) and formal architecting methods for systems decomposition and holistic analysis, with focus on their application to the identification of sources of uncertainty and ambiguity in the lifecycle of a system (supporting thesis objective n.1);
- **Multidisciplinary Design Optimization** (Section 2.3.2) as a framework for the exploration and evaluation of system architectures, with particular emphasis on optimization techniques under uncertainty (Section 2.3.3). Pareto and Fuzzy Pareto and Monte Carlo Analysis are discussed as tools for the exploration of design spaces under stakeholder ambiguity (supporting thesis objectives nn. 2-4);
- **Expert Elicitation** (Section 2.3.5) as a set of tools for qualitative and semi-quantitative encoding of expert judgments in the assessment of value of system architectures under stakeholder ambiguity (supporting thesis objective n.2);

- **Uncertainty Management Strategies** in engineering systems, and **Decision-Making Theory** for the analysis of complex dicisions and development of recommendations to decision-makers (supporting thesis objective n.5).

Table 1 Literature in Engineering Systems relevant to the proposed doctoral thesis

| **Research Objectives** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| | Identify potential sources of ambiguity in the value delivery and tradespace exploration processes. | Characterize and model the impact of the identified sources of ambiguity on the beneficial attributes that contribute to value as delivered to stakeholders, while satisfying their needs. | Identify and test the effectiveness of strategies aimed at mitigating the downside effects of ambiguity while exploiting its potential upside opportunities. | Down-select preferred system architectures that demonstrate being more resilient to ambiguities while still delivering value to stakeholders. | Develop recommendations to decision-makers to support final decisions concerning the selection of a system architecture for the enterprise of interest. |
| **Associated Literature Themes in Engineering Systems** | Systems Architecting (Section 2.3.1) | Multidisciplinary Design Optimization (Section 2.3.2)<br>Optimization under Uncertainty (Section 2.3.3)<br>Expert Elicitation (Section 2.3.5)<br>Uncertainty Management (Section 2.3.4) | | | Systems Architecting (Section 2.3.1)<br>Decision-Making Theory (Section 2.3.5) |

## 2.1. Definitions of Uncertainty and Ambiguity

The term uncertainty can be defined as "*liability to chance or accident*", "*doubtfulness or vagueness*", "*want of assurance or confidence; hesitation, irresolution*", and "*something not definitely known or knowable*" (Murray 1961); uncertainty "*applies to predictions of future events, to physical measurements already made, or to the unknown.*" (Wikipedia 2011). *Ambiguity* is a particular instance of uncertainty, and is defined as "*uncertainty about probability, created by missing information that is relevant and could be known.*" (Camerer and Weber 1992). Klir and Folger further classify ambiguity into *nonspecificity of evidence*, *dissonance in evidence*, and *confusion in evidence* (Klir and Folger 1988).

An exhaustive classification of uncertainty in economics, decision making, management, system analysis, policy, risk analysis, physical science and engineering is provided by Thunnisen (Thunnisen 2003). Several taxonomies of uncertainty have been proposed in the literature (Hastings and McManus 2004; Earl C and Eckert 2005; de Weck, Eckert et al. 2007). Earl distinguishes between *known uncertainties*, *unknown uncertainties*, *uncertainties in the data* and *uncertainties in the description* (Earl C. and Eckert

2005, 174). Hastings classifies different sources of uncertainty: *lack of knowledge* and *lack of definition*, and distinguishes between *known unknowns* and *unknown unknowns* (Hastings and McManus 2004).

In this thesis, ambiguity in stakeholder objectives according to those taxonomies can be classified in uncertainties in the description, due to both known and unknown unknowns. An example of known unknown is budget uncertainty (as it is impossible to know with certainty how budget allocations vary in future times), and an example of an unknown unknown is an abrupt policy change due to changed political conditions (for instance the occurrence of a war), or a breakthrough scientific discovery that changes the priority of scientific objectives in a space mission (for instance, the discovery of forms of life on a planetary surface). De Weck distinguishes between *endogenous* and *exogenous uncertainties* (de Weck, Eckert et al. 2007), depending whether their source lies within or outside of the boundary of the system of interest (Figure 10); ambiguities in stakeholder objectives can be either endogenous or exogenous. An example of endogenous ambiguity is in the use context, that is the functional intent of the system of interest. An example of exogenous ambiguity is the political and cultural context of a system.

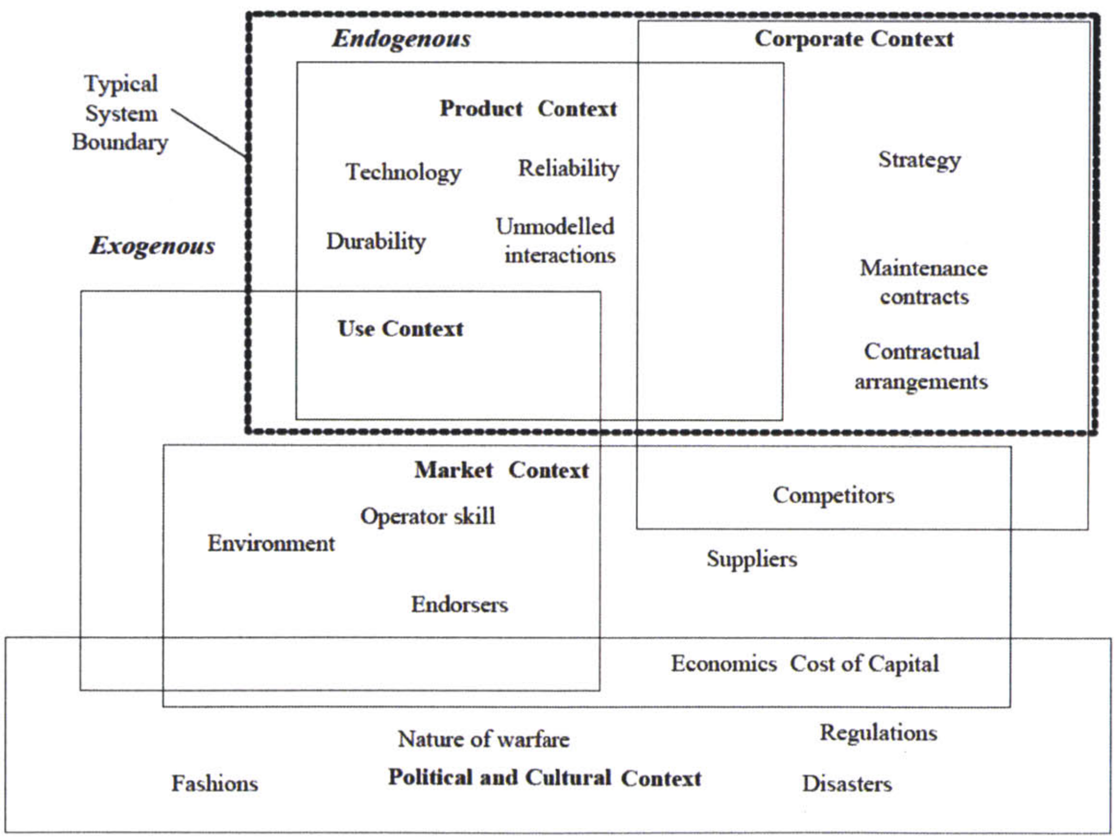



Figure 10 Endogenous and exogenous uncertainties (adapted from (de Weck, Eckert, and Clarkson 2007))

## 2.2. Ambiguity and Uncertainty beyond Engineering Systems

Ambiguity and uncertainty are themes that have been characterized initially in other disciplines than systems engineering and engineering design. In this section we provide an overview of the main themes in the literature, focusing the attention on concepts relevant to the assessment and mitigation of ambiguities in stakeholder objectives. For each disciplinary field we report they key references that are relevant to the topic under investigation.

### 2.2.1. Political Science

Academic research in political science and problems encountered in policymaking are often faced with the question of management of risk and uncertainties. In the policy domain, uncertainties are discussed in the field of *risk shielding* (Oye 2010). In particular, the debate over risk shielding hinges on the extent to which government and policymakers should shield against hazardous risks to the population. The fight in political science on risk management in policymaking centers around two different approaches: a *libertarian* (or *laissez-faire*) approach, as advocated by (Sapolsky 1990) and (Viscusi 2005), and a *regulatory* approach, based on the use of the *precautionary principle* (Harremoes 2001). (Morgan 1993) provides an intermediate approach to risk management in policymaking, advocating different approaches to policymaking based on the nature of the risk being considered – making a distinction between *known* and *unknown* risks – and based on whether the exposure to risk is on a voluntary or involuntary basis. The literature in this field provides a set of qualitative tools and guidelines for policymaking under uncertainty; quantitative tools used in policymaking are described in the decision-making theory literature, which is surveyed in successive sections of this chapter.

### 2.2.2. Finance and Economics

The analysis of uncertainty in finance and economics research traces its root in the seminal works of Von Neumann in game theory (Von Neumann and Morgenstern 1944) and Knight in uncertainty and risk (Knight 1965). It must be noted that Knight was the first to distinguish between *risks*, i.e. uncertainties with known probabilities of occurrence, and *uncertainties* (*Knightian uncertainties*), i.e. uncertainties with unknown probabilities of occurrence. Uncertainty research in economics and finance provides qualitative and semi-quantitative tools for the analysis of markets, improving the way in which investments are made, using *modern portfolio theory* (Markowitz 1999) and associated tools such as the *Capital Asset Pricing Model* (CAPM) (Sharpe 1964; Lintner 1965; Mossin 1966) and financial options (Black and Scholes 1973).

### 2.2.3. Management

Literature in management science has explored extensively in a qualitative way both themes of uncertainty and ambiguity. The focus of this literature is in the development of business strategies under uncertainty. Courtney et al. classify uncertainty in strategy planning in four levels, according to the degree of uncertainty to be faced (Courtney, Kirkland et al. 1997). From the lowest (level 1) to the highest (level 4) degree of uncertainty, they distinguish between *clear-enough futures*, *alternate futures*, *a range of futures* and *true ambiguity*. They note that level 4 uncertainties (true ambiguity) is often encountered in early stages of strategy planning, and it is often reduced to lower levels of uncertainty. They identify three strategic postures in management under uncertainty: *shape the future*, *adapt to the future* and *reserve the right to play*, implemented using three different types of management actions (*no-regret moves*, *options* and *big bets*) and provide guidelines on their use according to the level of uncertainty being faced (Courtney, Kirkland et al. 1997). Brandenburger and Nalebuff apply game theory to strategy planning under uncertainty, discussing the options available to managers to shape strategies by "changing the game", identifying *lose-lose* situations and transforming them into *win-win* strategies (Nash 1950), based on a value-net framework (Brandenburger and Nalebuff 1995). McGrath and MacMillan propose the idea of *discovery-driven planning*, where strategies are phased over time to allow uncertainty to unfold and adapt decisions accordingly (McGrath and MacMillan 1995) – analogously of what is discussed in the engineering section of this literature review in real option analysis and phased development strategies (de Neufville, de Weck et al. 2004; De Weck, De Neufville et al. 2004).

### 2.2.4. Engineering Design

Uncertainty in engineering has been initially treated in the discipline of *risk management* (Kumamoto and Henley 2000). The traditional focus of uncertainty in engineering are the uncertainties "in" the problem, looking only at the downside risk effects of such uncertainties - in performance, cost and schedule - and characterizing their likelihood of occurrence and impact. A semi-quantitative tool used in this context is the *risk matrix* (Morgan 1993), such as the one shown in Figure 11; the horizontal axis of the matrix measures the impact of the risk being assessed, and the vertical axis its likelihood of occurrence. The use of risk matrices in risk management has been criticized (Cox 2008): since they are based on qualitative assessments, they cannot provide an objective judgment of risk threats, and for the same reason they offer a poor resolution in distinguishing risks.

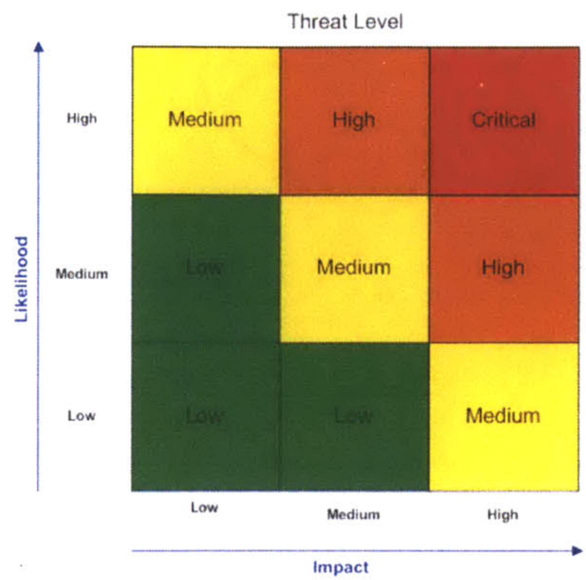



Figure 11 Example of risk matrix

Another traditional application of uncertainty analysis in engineering is reliability analysis aimed at the estimation of margins of safety (Ditlevsen 1982). Margins are used on uncertain variables of interest; an example in structural engineering is the sizing of a beam under uncertain loads or uncertain structural properties (Ganzerli and Pantelides 1999), or the design of buildings under seismic uncertainty (Veneziano, Agarwal et al. 2009). Taking margins is the traditional engineering approach to hedge uncertainty; however, it implies an overhead which has impacts on cost and performance: consider for example the overhead on gross liftoff mass of a launch vehicle given by the margins of safety on its structures.

Uncertainty analysis has found an ample breadth of applications in controls engineering. As reference examples, here we mention the control of dynamical systems under environmental uncertainty (Yang, Minai et al. 2004) and the disciplinary field of adaptive controls (Corless, Leitmann et al. 1987). In particular, a mathematical model that has found several applications in modeling uncertainty in this domain is that of Markov Decision Processes (Puterman 1994) (MDP). An MDP is a discrete time stochastic control process. Systems are modeled as a set of possible states, within which there are state transitions and associated transition costs (Figure 12 provides an example of a two-state MDP). MDPs can be used to model systems which behavior is partly random and partly controlled by an agent. MDPs are usually solved by means of dynamic programming (Bellman 1957), therefore implying that system states are path independent (i.e. the outcome at every state does not depend from the path taken to reach that state). A category of interest of MDPs is that of Partially Observable Markov Decision Processes (POMDP) (Monahan 1982), where the knowledge of possible states and/or transitions is also subject to uncertainty.

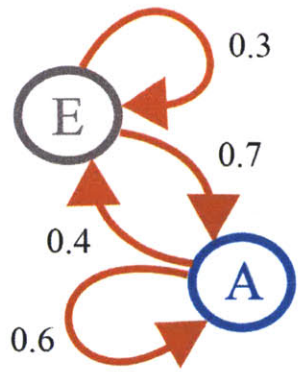



Figure 12 Example of two-state MDP (image source: Wikipedia)

Operations Research (OR) is another field of interest where uncertainty analysis has been applied extensively; problem examples in this domain are in logistics and supply chain management under demand uncertainty (Petrovica, Royb et al. 1998), and formulations of the classical OR problems under uncertain demands such as the Traveling Salesman Problem (Flood 1955), the Warehouse Location Problem (Baumol and Wolfe 1957) and the Knapsack Problem (Sinha and Zoltners 1977). Heyman provides an ample overview of stochastic models developed for OR problems (Heyman and Sobel 2004).

## 2.3. Ambiguity and Uncertainty in Engineering Systems

This section reviews the relevant literature concerning the study of ambiguity and uncertainty in engineering systems. As mentioned previously in this document, while uncertainties "in" the problem have been studied comprehensively in engineering systems, this is not the case of ambiguity (uncertainties "on" the problem), where this topic has been considered thoroughly or considered only using qualitative approaches.

### 2.3.1. Systems Architecting

The context in which this thesis operates is within the emerging body of literature in systems architecture, which is the discipline that provides "*an abstract description of the entities of a system and the relationships between those entities*" (Crawley 2008). The literature in systems architecture includes formal languages for system decomposition, such as Unified Modeling Language (UML) (Booch, Rumbaugh et al. 1996) and Object Process Modeling (OPM) (Dori and Crawley 2002), and quantitative methods for tradespace exploration (Ross and Hastings 2005). Koo developed a meta-language for systems architecting based on OPM, called *Object Process Networks* (OPN) (Koo 2005) (Figure 13); building on his work, Simmons developed a framework for quantitative, decision-based systems architecting, based on a method called the Architecture Decision Graph (ADG) (Simmons 2008) (Figure 14).

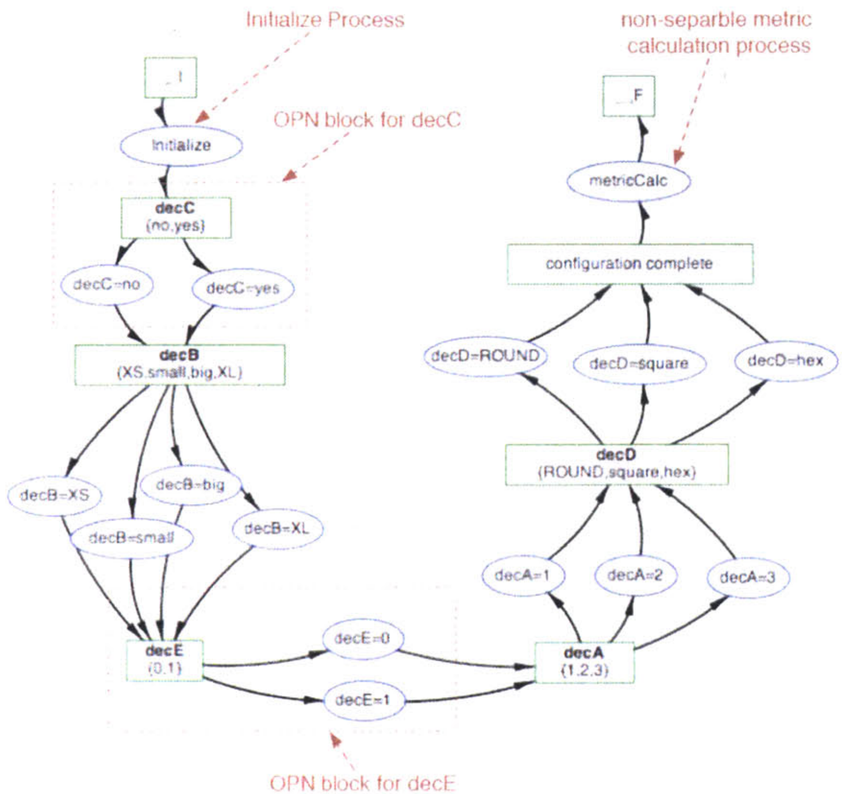



Figure 13 OPN Example (image source: (Simmons 2008))

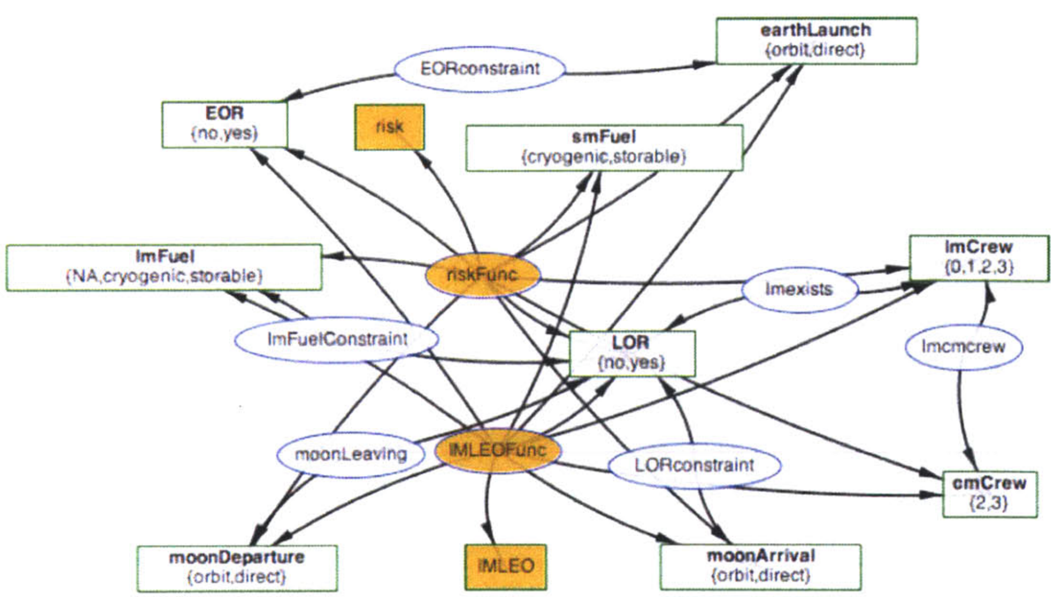



Figure 14 Apollo ADG Example (image source: (Simmons 2008))

Both OPN and ADG are used to perform tradespace exploration, based on a three step approach: 1) generation of architectures using a full enumeration approach, 2) evaluation of architectures and 3) identification of Pareto-efficient architectures (de Weck 2009). (Hastings, Weigel et al. 2003) proposed a systems architecting methodology accounting for uncertainty using portfolio theory, looking at the impact of traditional uncertainties "in" the problem on systems architecting, with an application to space systems developed for commercial purposes (a satellite constellation for telecommunications). This method can be used to determine portfolios of systems robust to uncertainty, but does not include an assessment of the impact of ambiguity in stakeholder objectives, and does not consider the value of flexibility in engineering systems (as discussed later in this chapter), and it is only applied to architectures represented by purely discrete design vectors, being formulated as a portfolio optimization.

### 2.3.2. Multidisciplinary Systems Design Optimization

The architecting methods described above rely on full enumeration of architectures; however, those methods fail when the size of the feasible design space is large enough so that computational times would be prohibitive for full enumeration. A solution to this problem comes from the literature in Multidisciplinary Design Optimization (MDO) (Agte, de Weck et al. 2010), that provides optimization-based methods for exploration of large design spaces. MDO is a discipline that has been traditionally introduced for detailed system design, and its approaches are recently being implemented in large-scale systems architecting problems; the author of this thesis developed a MDO framework for systems architecting of launch vehicle families based on a hybrid optimization framework (Aliakbargolkar and Crawley 2010). Several MDO approaches have been developed over the years, such as Braun's Collaborative Optimization (Braun and Moore 1999) and others: Tedford provides an overview and a benchmark of multiple MDO algorithms, making use of different strategies for problem decomposition and optimization approaches (Tedford and Joaquim 2007).

### 2.3.3. Optimization under Uncertainty

The OPN and ADG architecting methods assume deterministic models for architectural evaluation, and do not account for uncertain environments; on the other hand, the MDO community developed several approaches to account for uncertainty and ambiguity. This literature falls into the sub-field of Optimization under Uncertainty. Optimization routines can be embedded into an MDO framework, therefore allowing uncertainty assessments in the overall architecting process. The seminal work in optimization under uncertainty was conducted by Dantzig in his *Linear Programming* (LP) formulation under uncertainty (Dantzig 1955), based on a *stochastic programming with recourse* approach (Kall and Wallace 1994; Birge and Louveaux 1997). Sahinidis provides a comprehensive overview of optimization methods under uncertainty (Sahinidis 2004), including *stochastic integer programming* (Dempster, Fisher et al. 1981; Spaccamela, Rinnooy Kan et al. 1984), *stochastic nonlinear programming* (Bastin 2001), *robust stochastic programming* (Mulvey, Vanderbei et al. 1995) and *fuzzy programming* (Bellman and Zadeh 1970, 141), (Tanaka and Asai 1984).

### 2.3.4. Uncertainty Management and Decision-Making Theory

Management of uncertainties in engineering systems is an emergent body of literature, dealing with approaches to cope with uncertainty in engineering systems. Two main approaches have been proposed: the implementation of *robustness* (Phadke 1995), (Taguchi 1986) and the implementation of *flexibility* options in the system of interest (de Neufville, de Weck et al. 2004). Among its objectives, the research proposed for this doctoral thesis intends to implement both approaches as management strategies for ambiguity in stakeholder objectives, in order to verify their effectiveness in this context. De Weck demonstrated the value of implementing flexibility options in a satellite constellation architecture (De Weck, De Neufville et al. 2004), using *lattice analysis* to describe propagation of uncertainty over the lifecycle of the architecture and advocating for a *phased development approach* for large-scale systems to hedge endogenous and exogenous uncertainties and capture upside opportunities due to uncertainty. Furthermore, Silver and de Weck proposed a network-based approach to analyze flexibility for complex evolutionary large-scale systems, the Time-Expanded Decision Networks (Silver and de Weck 2007). More recently, *screening models* based on a Monte Carlo simulation framework have been proposed for the evaluation of flexibility options in engineering systems (Lin 2008). Screening models have the advantage of having less constraints on the formulation of the problem than other methods (for example, they do not require the system representation to be path independent), assuming the problem is formulated and decomposed properly to be resolved in reasonable computational times, but they do not include an assessment of the impact of ambiguity of stakeholder objectives in the evaluation of system architectures.

### 2.3.5. Expert Elicitation and Decision-making Theory

Architecting methods allow the identification of Pareto-efficient architectures, as described previously; they can be complemented with quantitative tools from decision-making theory (Edwards 1954; Bellman and Zadeh 1970; Keeney and Raiffa 1976; Kahneman and Tversky 1979; Zeleny 1982; Howard 1988; Dyer, Fishburn et al. 1992; Roy and McCord 1996). A tool of practical use in this context is the development of *decision trees* (Howard 1988) (Figure 15), which require a formal choice-decision to enumerate possible scenarios, associated expected outcomes and subjective probabilities of occurrence.

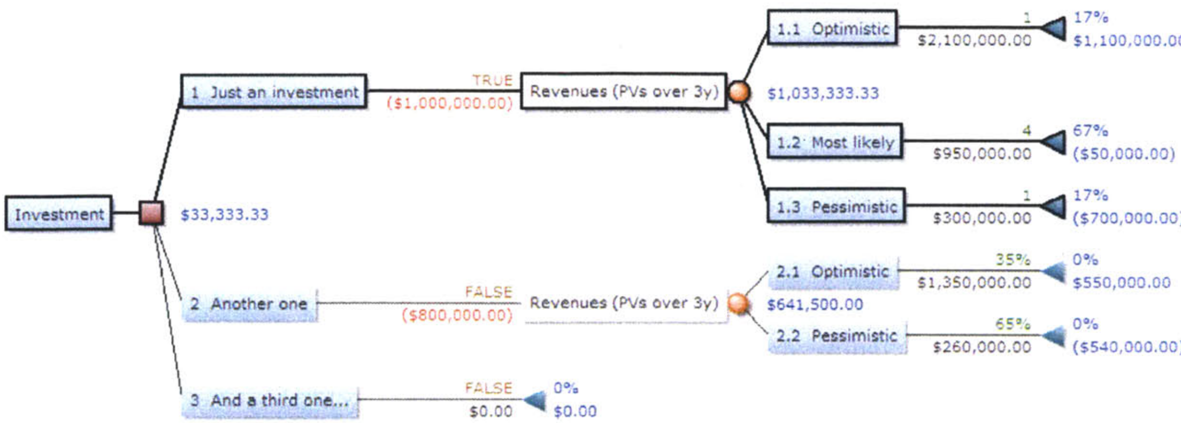



Figure 15 Example of decision tree analysis (image source: Wikipedia)

Recommendations based on decision-tree analysis are based on the maximization of expected value criteria (Meyer 1987). Decision tree analysis, however, has several limitations. In fact, it requires a "discretization" of the range of possible outcomes in a set of discrete occurrences. Furthermore, full enumeration of full scenarios is prohibited if the number of possible scenarios is too large; this issue is often overcome with dynamic programming approaches (Bellman 1957), which however require the decision-tree representation to have specified characteristics such as path independence. Most importantly, for the purposes of modeling ambiguity in this thesis, the main limitation of traditional decision trees is that they require a deterministic knowledge of subjective probabilities of occurrence for each scenario.

Decision-making support often requires the synthesis of subjective opinions, for instance, in the definition of value metrics in systems architecting. Multi Attribute Utility Analysis (MAUA) (Keeney and Raiffa 1976) and the Analytical Hierarchy Process (AHP) (Forman and Gass 2001) (Figure 16) are tools that have been applied for decision-making purposes in several disciplinary fields.

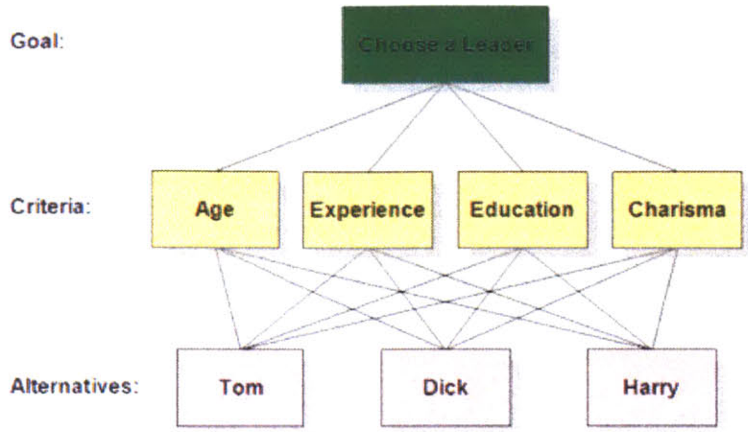



Figure 16 AHP hierarchy example (image source: Wikipedia)

While MAUA has been applied to systems architecting previously (Ross and Hastings 2005), little research has been done on how to define utility under ambiguous stakeholder objectives – where the definition of value-based utility functions is unclear. Both methods have known limitations. MAUA encounters challenges in preference elicitation when applied to the evaluation of attributes with no monetary equivalents. AHP on the other hand is prone to rank reversal issues when new attributes are considered in the tradespace (Schenkerman 2003). None of these two methods deal when ambiguity is introduced in group decision-making.

Expert elicitation is the discipline concerned with the synthesis of expert knowledge and opinions aimed at providing tools for engineering and multidisciplinary analysis. Expert elicitation has been historically used for the elicitation of probabilities of occurrence in safety analysis, such as the famous Rasmussen report on nuclear reactor safety (Rasmussen 1975). Other historical applications of expert elicitation include expert assessments synthesis for complex systems analysis (NAS 1975).

Expert elicitation techniques are of particular interest for engineering systems, as they allow the quantification of subjective metrics that are of paramount importance to the design process. Elicitation techniques has been used to estimate experts' preference structures for multi attribute analysis, such as the ratio method (Edwards 1977), the swing method (von Winterfeldt and Edwards 1986) and the tradeoff method (Keeney and Raiffa 1976). Focus group methods (Terpstra, Lindell et al. 2009) are routinely used for elicitation of expert knowledge. While focus group and conventional group-decision making processes are effective in improving convergence towards consensus, they suffer adverse behavioral effects originating from peer pressure and hidden agendas. Focus groups are also ineffective in presence of the highest degree of ambiguity originated by the unknown (such as forecasting of future events). The Delphi method is a qualitative tool that has been originally developed to this end, to improve forecasting in expert policy-making (Rowe, Wright et al. 1991; Adler and Ziglio 1996; Rowe and Wright 1999). Delphi synthesizes expert knowledge by anonymous elicitation of experts, while reducing adverse peer-pressure effects through anonimity in expert elicitation. While Delphi has been used in the context of forecasting and decision-making, this thesis engineers the Delphi process in a quantitative form and implements it in the context of decision making, assessing advantages and disadvantages.

## 2.4. Identification of Research Gaps

This section identifies the research gaps to be address by this dissertation. Four gaps are identified, both at the conceptual and methodological level: *Identify*, *Characterize*, *Mitigate* and *Integrate*.

The first gap (*Identify*) to be addressed by this thesis is to identify ambiguity in architecting systems with a high degree of innovation and highly exploratory objectives. While (Ross and Hastings 2005) described the impact of uncertainty in the definition of system requirements, they did not discuss comprehensively the problem of ambiguity in the description of the systems to be designed – and how to identify ambiguity as such - leaving room for a research opportunity in this field. (Hastings, Weigel et al. 2003) discussed an application of financial portfolio theory to incorporate uncertainty in systems architecting and select engineering portfolios with different risk aversion profiles. However, they assume known sources of uncertainty, and do not address uncertainty in its highest degree, that is ambiguity. This thesis identifies potential sources of ambiguity in systems architecting by means of ontological analysis, and develops a framework to identify, classify and mitigate ambiguities, therefore covering this gap in the literature.

The second gap to be addressed (*Characterize*) is to characterize ambiguity as an adverse factor to effective systems architecting. While traditional uncertainty has been investigated extensively in the literature, less efforts where spent in characterizing ambiguity beyond the field of forecasting techniques. This thesis provides a framework for management of ambiguities, called the descriptive Systems Architecting Management Framework, and describes a taxonomy for classification of reducible and irreducible ambiguities, as described in Chapter 3.

The third gap to be investigated (*Mitigate*) is the mitigation of reducible and irreducible ambiguities in the functional intent of a systems architecture. The research is defined as a problem of requirements definition under stakeholder ambiguity. This thesis presents a framework for quantitative analysis the value delivery process (Crawley 2008) of a system, including the assessment of ambiguity in the definition of stakeholder needs and in the functional intent process. It presents and informs strategies for effective mitigation of multi-domain ambiguities in systems architecting.

The fourth gap to be fulfilled (*Integrate*) is the lack of integration of ambiguity expert elicitation techniques with formal system architecting methods in conventional systems engineering practice. These steps are treated are separate in conventional lifecycle models. Figure 17 shows examples of waterfall lifecycle processes taken from the INCOSE Systems Engineering Handbook that highlight this issue. Typical models include requirements definition as upstream processes – such as NASA's Pre-Phase A processes or DoD user needs definition process - with no feedback loops between requirements definition tradespace exploration towards concept definition. Few iterations are performed upstream in spiral life-cycle models (as shown in Figure 18), but with little iterations of requirements definition phases and no explicit integration with down-stream spiral processes. This gap is filled in this thesis by integrating quantitative expert elicitation for requirements definition with traditional design space exploration models. The framework presented in the thesis allows the exploration of large design spaces through the integration of hybrid MDO approaches.

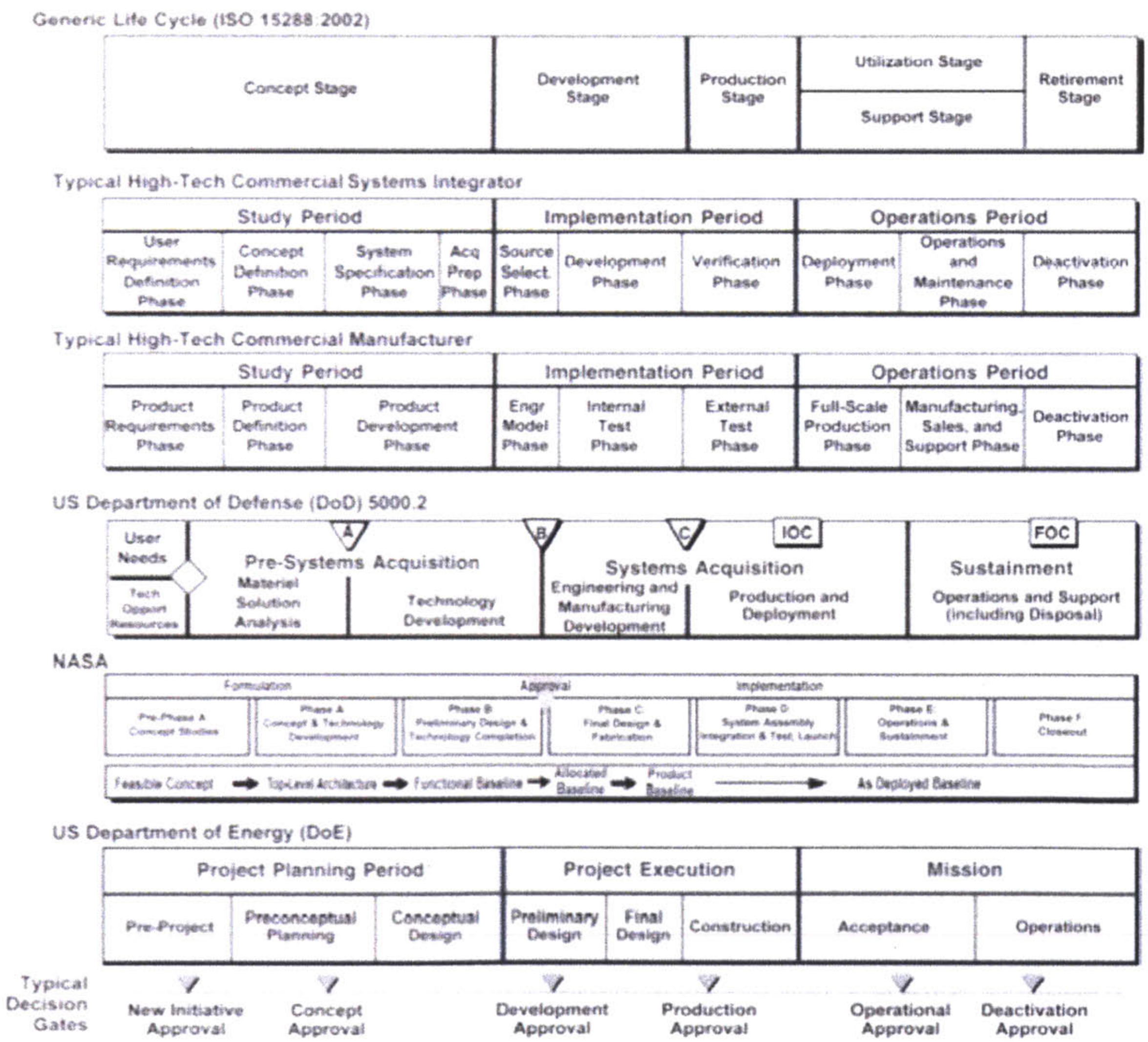



Figure 17 Examples of life-cycle processes (image source: (INCOSE 2010))

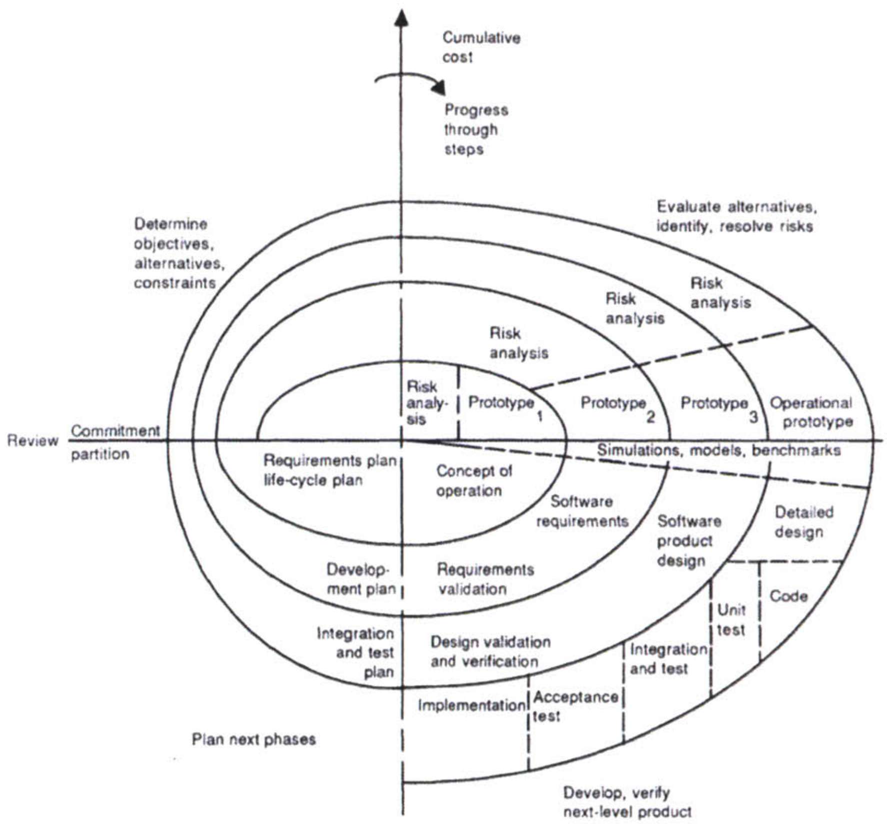



Figure 18 Spiral model for system development (image source: (Boehm 1988))

## 2.5. Summary

This chapter presented a review of literature relevant to the problem of the systems architecting under ambiguous stakeholder objectives. Thesis objectives are framed in context to relevant literature of ambiguity and uncertainty in engineering systems analysis and other disciplinary fields – including political science, finance and economics, management and engineering design.

The literature review revealed four conceptual and methodological gaps concerning characterization, defined as Identify, Characterize, Mitigate and Integrate. Following the identification of research gaps, this chapter defined the research opportunity that has been pursued in this thesis. Based on these premises, Chapter 3 describes the comprehensive approach for systems architecting that has been developed to fill research gaps that have been identified.

# Chapter 3 : Comprehensive Approach for Systems Architecting under Ambiguous Stakeholder Objectives

Chapter 1 described ambiguity as a threat to successful systems architecting. The literature review in Chapter 2 has shown how multiple fields in science, engineering and social sciences cope with ambiguity. Ambiguity has been characterized as the highest possible degree of uncertainty in systems architecture. The review of the state of the art revealed gaps in the identification, characterization and mitigation of ambiguities in systems architecting. This chapter fills the fourth research gap by presenting a comprehensive approach for systems architecting under ambiguous stakeholder objectives. The chapter presents the approach that has been developed to integrate upstream and downstream architecting processes in a unified framework, to analyze and mitigate ambiguities as they present themselves in systems architecting.

## 3.1. Ontological Analysis for the Ambiguity Identification in Upstream Systems Architecting Processes

In his doctoral dissertation, Simmons described systems architect as responsible for the transformation of a set of needs and goals into a systems architecture (Simmons 2008). This section presents an ontological analysis of upstream systems architecting processes. The goal of the analysis is to identify potential sources of ambiguity affecting the system architecting process, with emphasis on upstream processes of elicitation of a functional intent and translation into a corresponding systems architecture. The analysis in this section is analog to Suh's axiomatic approach to systems design (Suh 1998). However, for the scopes of this ontological analysis the focus is on hierarchical mapping only, and the analytic tools of choice are set theory and first-order propositional logic, instead of Suh's matrix operation relationships.

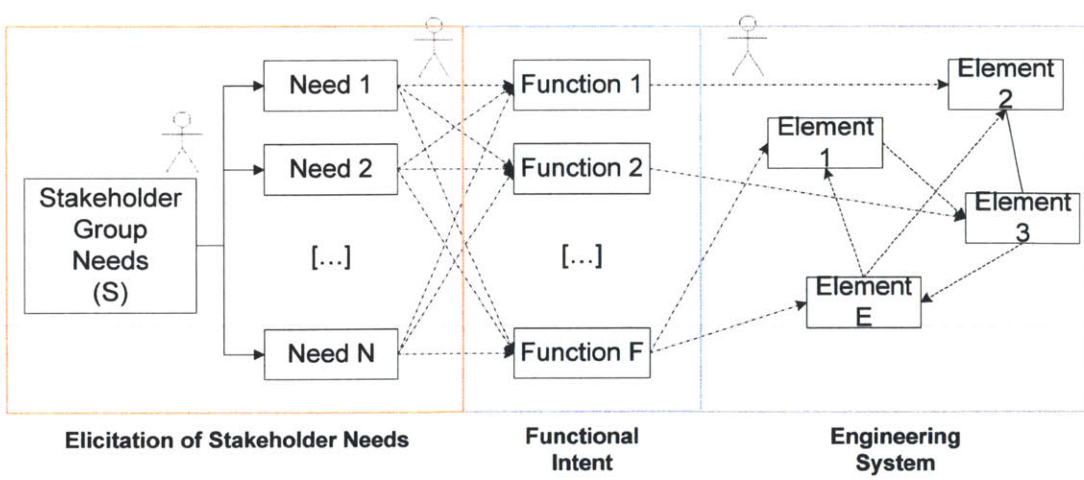



Figure 19 Functional view of upstream systems architecting processes

Figure 19 shows a functional view of upstream systems architecting processes. On the left hand side of the figure are *stakeholder group needs* agreed by a consensus-driven group S formed by E stakeholders, each eliciting individual needs $s_{ie}$: $S = \bigcap\left\{\left\{s_{11}, s_{21}, \ldots, s_{S1}\right\}, \left\{s_{12}, s_{22}, \ldots, s_{S2}\right\}, \ldots, \left\{s_{1E}, s_{2E}, \ldots, s_{SE}\right\}\right\}$.

Group needs are decomposed by system architect A in needs perceived by stakeholder group S: $N\big|_S^A = N\left\{N_1, N_2, \ldots, N_N\right\}\big|_S^A$. Needs are mapped by the system architect to a set of intended system functions $F\big|^A = F\left\{F_1, F_2, \ldots, F_F\right\}\big|^A$ through a *function-need mapping* $M_{F\to N}\big|^A \leftrightarrow N = M_{F\to N}\left(F\right)\big|^A$.

System functions are mapped to a set of elements of forms $E\big|^A = E\left\{E_1, E_2, \ldots, E_E\right\}\big|^A$ through a *form-function mapping* $M_{F\to F}\big|^A \leftrightarrow N = M_{F\to F}\left(F\right)\big|^A$.

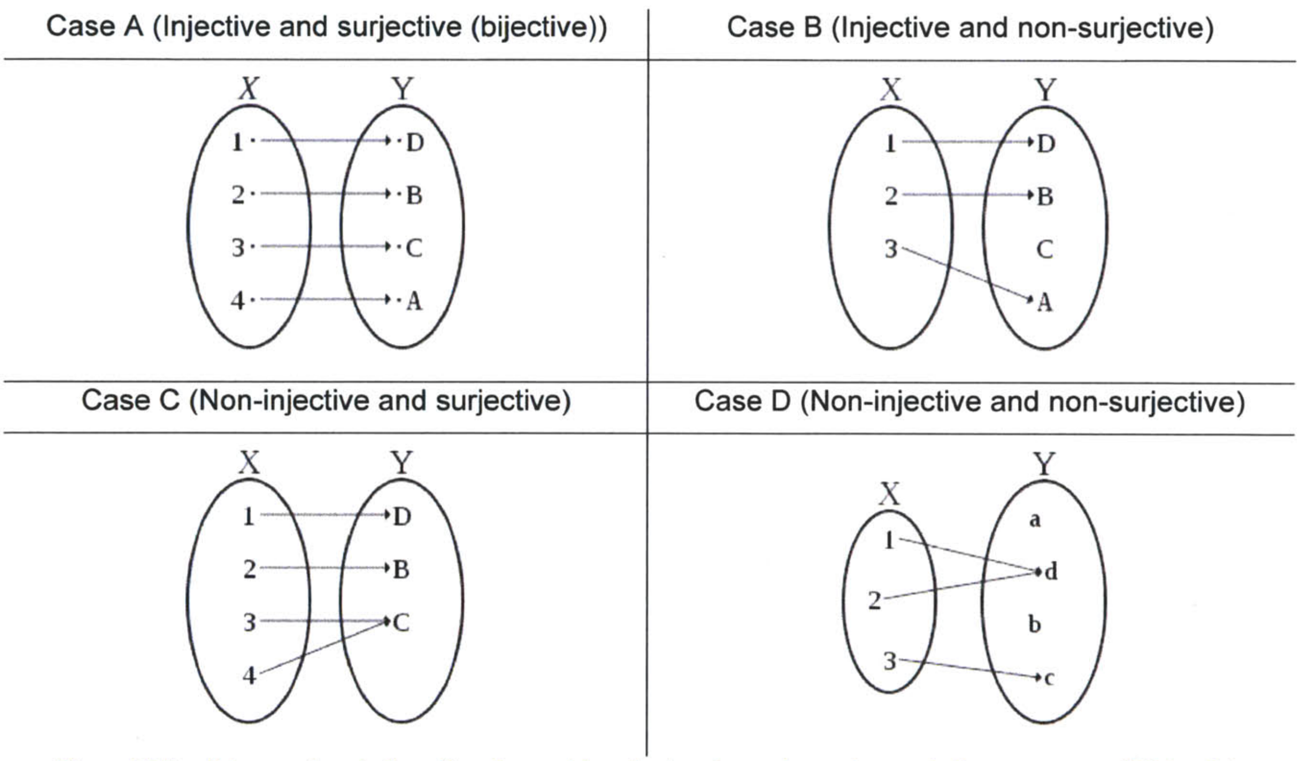



Figure 20 Possible mappings in form/function and function/need mapping assignments (images source: Wikipedia)

Figure 20 shows possible functional assignments that can be found in function-need and form-function mappings. *Acceptable* function-need and form-function mappings are defined as mappings that are always *surjective* (case A and C in the Figure), that is, where every function/form is mapped to *at least* one need/function respectively. Non-surjectivity indicates incomplete mapping by the system architect, where, for instance, not all elements of form are mapped to respective system functions they are supposed to perform. Mappings are *injective* (case A and B in the Figure – where only A is acceptable due to surjectivity) when needs/functions and functions/forms are in *one-to-one* correspondence. Functional commonality (i.e. the embodiment of multiple functions in one element of form) is represented by *non-injective* mappings (case C and D in the Figure – where only C is acceptable on surjectivity grounds). Figure 21 shows different types of form/function mappings – which can also be interpreted as function/need mappings for this discussion. Form (function) elements sharing multiple functions (needs) are represented by non-injective mappings, representing the case of functional commonality. Function sharing across multiple elements of form (and likewise, need sharing across multiple functions) is represented by inverse, non-injective forms/functions (function/needs) mappings. Function sharing represents both the case of single functions performed by multiple elements of form independently (such as the case of redundant systems), and the case of single functions that emerge from the interaction by multiple elements of forms (emergent system properties).

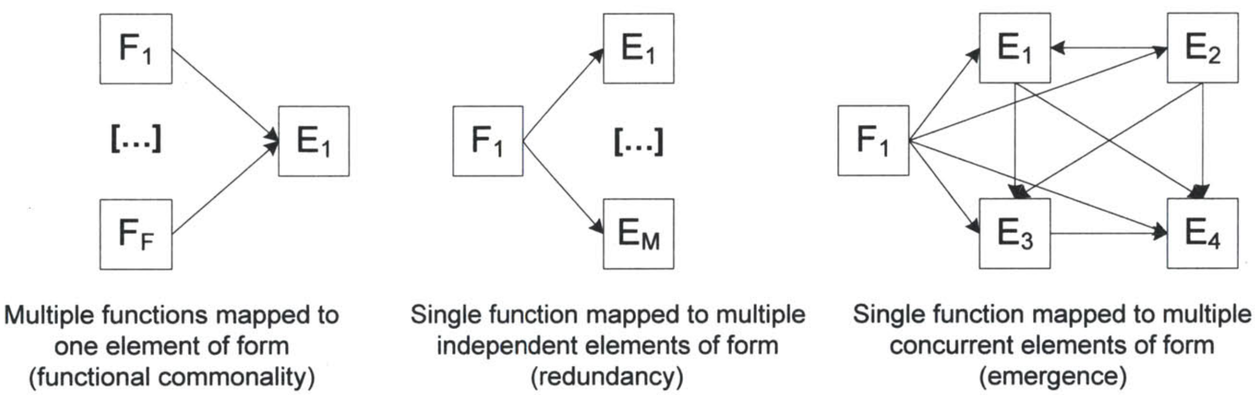



Figure 21 Types of Form/Function Mapping (also applicable to Function/Need mappings)

Elements of form are connected each other through $T$ interface types (such as mechanical, electrical, fluid and logical interfaces), represented by associated *affinity matrices* $\underline{\underline{I}}\big|_t = \left[I_{ij}\right]\big|_t \;\; \forall t \in T$, where

$$I_{ij} = \begin{cases} 0 & \leftrightarrow \quad \text{element i IS NOT connected to element j} \\ 1 & \leftrightarrow \quad \text{element i IS connected to element j} \end{cases}$$

Constraints between elements of form $\left\{E_1, E_2, \ldots, E_E\right\}\big|^A$ can be expressed with first-order logic statements (Smullyan 1995) using *conjunction* ($E_1 \wedge E_2$, i.e. AND), *disjunction* ($E_1 \vee E_2$, i.e. OR), *implication* ($E_1 \rightarrow E_2$, i.e. IMPLIES), *biconditional* ($E_1 \leftrightarrow E_2$, i.e. IFF) and *negation* ($E_1 \neg E_2$, i.e. NOT) logical connectives.

Constraints can be of *mutual dependence* ("both element $E_1$ AND $E_2$ <...>"), *mutual exclusivity* (compatibility constraints of the form "either element $E_1$ OR $E_2$ <...>"), and *implication* ("element $E_1$ IMPLIES $E_2$). Spatial (*allocation*) and temporal (*precedence* or *scheduling*) constraints are defined with affinity matrices that are function of time and space $\underline{\underline{I}}\big|_t = \underline{\underline{I}}\big|_t(\vec{x},t)$.

Functions are connected each other through a *concept of operations*, where a subset of functions $F' \subseteq F$ is optionally constrained by a set of *precedence/scheduling constraints* defining links between *terminal functional events* (start/finish), as shown in Figure 21, analogously to what is done with project dependencies in project management practice (PMI 2004).

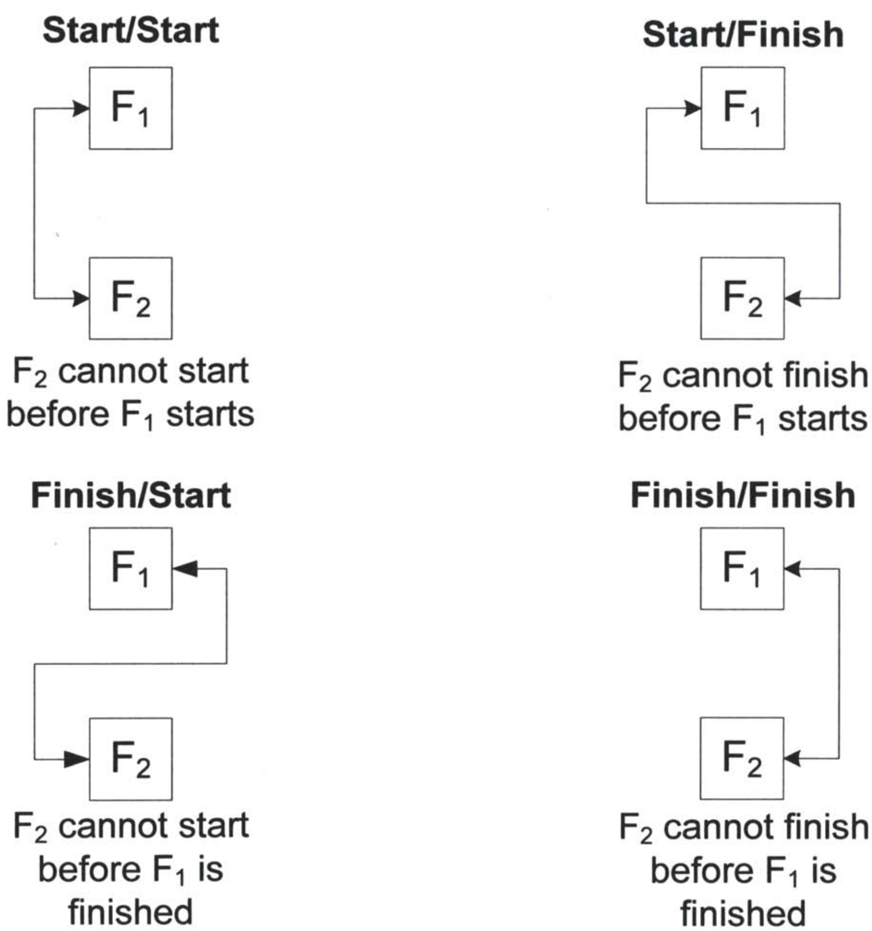



Figure 22 Precedence/Scheduling Constraints between System Functions applicable to Concepts of Operations

This thesis makes the following *fundamental assumption* on sources of ambiguity and the extent to which ambiguity affects system architectures:

**Potential sources of ambiguity are created in all upstream systems architecting processes where human agents interact together to define value, and define means of value delivery.**

In other words, this assumption is saying that all interaction opportunities among stakeholders (represented by stakeholder group S), and between stakeholders S and the system architect A are potential sources of ambiguity. Ambiguities are thought as externalities of group decision-making, such as adverse peer pressure and individual hidden agendas. We do not consider internal sources of uncertainty in this discussion (for instance in the definition of affinity matrices), as we focus the attention on ambiguity sources. However, an analog ontological analysis could be performed on downstream systems architecting processes to identify potential sources of uncertainty.

The fundamental assumption on ambiguity can be used in a backward examination of the ontological analysis exposed above to identify potential sources of ambiguity in upstream systems architecting processes. The following potential sources are identified:

- **Stakeholder group S - perceived needs (** $N\big|_S^A = N\{N_1, N_2, ..., N_N\}\big|_S^A$ **)**: note the use of the word *perceived* – stakeholders *perceive* needs, driven by policies, user needs, one-time events, the environment and so forth. Needs change over time, affected by the culture of the organization, leadership styles, exogenous influences, and occurrence of low probability events. The net result of ambiguity in this context is for stakeholders S and system architect A not to map real needs with stated needs through perception in a satisfactory way. Consider for instance the unexpected change in 2011 in the Swiss public policy for energy production, following the incident of the Japanese Fukushima nuclear reactor (Kanter 2011). Stakeholders' need perception changed dramatically after the occurrence of a low probability event bearing potentially catastrophic consequences. Abrupt changes come to a cost of policy failures in a political science sense, and introduce ambiguities in the perception process of the mapping between real and stated needs. Other sources of ambiguity in perceived needs are *hidden agendas*, defined as the dichotomy between *stated* and *desired* needs for a system architecture ("*not the requirements but the «desirements»*" (Ertekin 2012)). Another source of ambiguity is *peer pressure* in stakeholder elicitation, defined as the influence of stakeholders to peers of the same stakeholder group (such as the influence of senior scientists to junior scientists, and so forth).

- **Perceived set of intended functions** ( $F\big|^{A} = F\{F_1, F_2, ..., F_F\}\big|^{A}$ ): the job of system architects is to transform a set of perceived needs into a set of intended system functions, towards the definition of a system architecture (Simmons 2008). A source of ambiguity is then identified in transforming needs in functions. Such ambiguity can either be due to *unknown*, non accounted factors, or to non comprehensive consideration of all stakeholders in the need elicitation process.
- **Function/need mapping** ( $M_{F\to N}\big|^{A} \leftrightarrow N = M_{F\to N}(F)\big|^{A}$ ) and **Form/Function mapping** ( $M_{F\to F}\big|^{A} \leftrightarrow N = M_{F\to F}(F)\big|^{A}$ ): mapping processes are subject to ambiguity introduced by the system architect, due to unfocused, incomplete or incorrect definition or documentation of the mapping function. There are evidences of this type of ambiguity in the systems engineering literature. For instance, the INCOSE Systems Engineering Handbook defines this as ambiguity in initial system requirements for a system in its Development Stage (INCOSE 2010). Another source of ambiguity is identified in evolutionary changes of function/need and form/function mapping functions. This phenomenon is identified in the literature as *scope creep*, or *requirements creep*. The PMBOK of the Program Management Institute identifies two forms of requirements creep: *business scope creep*, and *feature (technology) scope creep* (PMI 2004).
- **Formal and Functional Constraints:** constraints between elements of form and functional constraints defined as a *concepts of operations* (conops) can be affected by the ambiguities defined above, therefore posing threats to the value delivery process from the architecture to stakeholders. Examples of ambiguities are in the definition of a concepts of operations or interface issues in systems of systems such a space awareness or space weather infrastructure, where multiple heterogeneous elements are supposed to cooperate together towards one goal. Ambiguous specification of the conops can, in principle, prevent systems cooperation and the achievement of desired goals.

This analysis identified several sources of ambiguity in upstream systems architecting processes by means of formal ontological analysis. Therefore, it is now possible to classify ambiguities according to their nature and mapping to systems engineering processes.

## 3.2. Classification of Ambiguities in Systems Architecting

Based on the ontological analysis discussed in Section 3.1, this section proposes a classification of ambiguities according to their inherent nature in the systems architecting process. This thesis identifies two fundamental classes of ambiguity: *reducible ambiguities*, and *irreducible ambiguities*, shown in Figure 23.

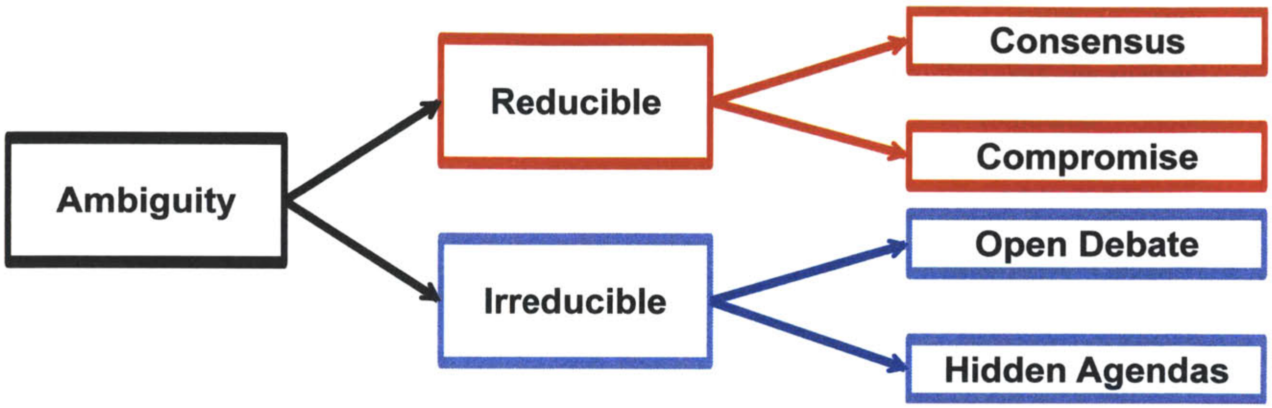



Figure 23 Classification of Ambiguities in Systems Architecting

*Reducible ambiguity* is defined as ambiguity generated by lack of understanding on *known* knowledge. Reducible ambiguity derives from confusion in stakeholder elicitation and definition of functional needs and mappings. This type of ambiguity is only apparent, as it can be reduced by appropriate mitigation efforts, as described in the next sections of this chapter. Nevertheless, non mitigated reduced ambiguity is a threat to systems architecting, as it impedes proper definition of the functional intent. Reducible ambiguity lies in areas where consensus and compromise among stakeholders are possible. Typically, this type of ambiguity affects highly specialized needs and functions, where a high degree of expert knowledge is required. Consider for instance the definition of needs related to a highly specific sub-field of science. Confusion arises as most stakeholders are not aware or do not understand said needs. Comprehensive composition of the representative stakeholder group and the use of a structured comprehensive systems architecting framework (such as the one proposed in this thesis) allow effective reduction of said ambiguity. Another example of reducible ambiguity is derived by definition of requirements in a planetary science mission. Scientists need to retrieve data to expand the knowledge in their science fields, whereas engineers have the need to design an architecture to deliver required performance, while meeting cost caps and other programmatic constraints. Those needs are often clashing, and poor understanding among stakeholders' views are sources of reducible ambiguity. Part of the job of the system architect is to bring a comprehensive analysis to the table and help reduce such ambiguities. The framework proposed in this thesis is a structured toolkit to do so.

*Irreducible ambiguity* is defined as lack of understanding on *unknown* knowledge. Ambiguity is the highest degree of uncertainty when it deals with unknown information, such as future policy changes, unknown scientific discoveries, unknown technological capabilities and so forth. Irreducible ambiguity is a double-edged sword, as it provides the most threatening challenges in systems architecture as well as the most rewarding areas of opportunities, such as breakthrough discoveries in science and the development of key enabling technologies pushing the boundaries of the feasible design space. Irreducible ambiguities include *areas of open debate*, and the embodiment of *hidden agendas* in perceived stakeholder needs. Groups of stakeholders might reach to illusional consensus when dealing with irreducible ambiguities, which is a threat if ambiguity is not explicitly recognized as such and related requirements not designed accordingly and kept under control over time. Examples of areas of open debate include definitions of scientific value, policy return, and intrinsic value associated with the selection of destinations for human space exploration. *Hidden agendas* are even more subtle ambiguities, are they can usually be traced as causes of cost growth and schedule slippage. Hidden agendas are driven by individual stakeholder interests, which steer stakeholder groups from rational elicitation of perceived needs. Hidden agendas are classified as irreducible ambiguities as they cannot be identified with absolute certainty, therefore preventing mitigation. However, identification of potential hidden agendas is key information to decision-makers and system architects should include such information as part of their functional analysis towards the definition of a functional intent.

Both reducible and irreducible ambiguities are surfaced through elicitation of expert knowledge from stakeholder groups. Expert elicitation, therefore, takes a central role in upstream systems architecting processes. The following section reviews and characterizes expert elicitation techniques, that can be used by system architects in systems architecting under explicit recognition of ambiguity in stakeholder objectives.

## 3.3. Expert Elicitation for Systems Architecting under Ambiguity in Stakeholder Objectives

Expert elicitation is a key process in upstream systems architecting. Expert elicitation techniques are used for the definition of perceived needs, the definition of intended system functions and related mapping processes, as discussed in Section 3.1. Three models for expert elicitation can be developed. Elicitation can be performed using *structured* (following a formal process defined *a priori*) or *unstructured* methods. Elicitation methods can either employ multiple iterations (*iterative* methods), or one-time assessments.

Finally, elicitation methods can either ask for anonymous contributions by experts (*anonymous* methods), or have experts identify their contribution to the process.

This section characterizes expert elicitation models across the taxonomy proposed above, and describes advantages and disadvantages of categories of expert elicitation methods.

Expert elicitation can be performed using one of the following conceptual models:

- Bottom-up elicitation
- Analogy-based elicitation
- Workgroup elicitation

*Bottom-up elicitation* is an open approach consisting in the involvment of scientific, technical and political communities at large in the definition of stakeholder needs. These methods includes workshops, open questionnaires, surveys and requests for proposals. Bottom up elicitation can be used to define needs for new systems, to redefine use of heritage systems or assess evolution options of existing systems. While bottom up methods are useful for assessing the needs across a large set of users, they are prone to the generation of reducible ambiguity due to the high volume of data to be processed and lack of coherence in definitions and preliminary assumptions. Bottom-up elicitation techniques are typically unstructured, non iterative, and can be performed with either anonymous or non anonymous elicitations of knowledge.

*Analogy-based elicitation* infers stakeholder needs and defines functional requirements based on retrospective analysis of analog systems that have been deployed for past applications. For instance, system architects can reverse engineer a remote sensing satellite architecture to infer stakeholder needs and associated functions to design in a new satellite constellation. The outcome of this type of elicitation depends significantly on individual expert knowledge of the system architect. Structured approaches such as formal systems decomposition languages (OPN (Koo 2005), OPM (Dori and Crawley 2002), ADG (Simmons 2008), UML (Booch, Rumbaugh et al. 1996)) and axiomatic system design frameworks (Suh 1998) can be used to inform analogy-based elicitation. While analogy-based approaches have advantages in reducing cost and elicitation schedule, they imply risks in neglecting ambiguities and emergent behaviors unique to the architecture to be designed. Analogy-based expert elicitation is conducted with structured or unstructured approaches, with multiple iterations. Anonymity is not a concern in analogy-based elicitation.

*Workgroup elicitation* consists in composing expert panels representative of stakeholders of interest, and elicit their knowledge towards definition of perceived needs and associated functional requirements.

Methods for workgroup elicitation include panel group meetings, interviews, questionnaires, and surveys. Structured approaches consist in quantitative methods such as utility theory (Fishburn 1970), decision tree analysis (Zeleny 1982), the analytic hierarchic process (Saaty 1994) and the development of rule-based expert systems (Ignizio 1991). Unstructured approaches are usually qualitative methods, such as open-ended interviews, or the Delphi method (Rowe and Wright 1999). Quantitative methods have the advantage of providing guidance for decision-making through rational frameworks. However, these methods imply underlying assumptions and analysis limitations that must be well known by the system architect for their effective selection and application. Qualitative methods offer the advantage of allowing unconstrained elicitation of knowledge. Of those, the Delphi method is of particular interest to this thesis. Delphi was originally developed during the Cold War by the RAND Corporation to design a military response to unknown enemy threats (Rowe, Wright et al. 1991; Rowe and Wright 1999), finding later applications in science and technology forecasting as well as policy-making. The key feature of the Delphi method is the ability of eliciting expert knowledge in iterative rounds. This is achieved by conducting structured surveys in *anonymous form*; the participants in a Delphi study do not know the identities of other participating experts. Anonymity allows participants to express their opinions while minimizing counter-productive behavioral aspects caused by high pressure situations such as science team meetings or by organizational hierarchy issues. As the Delphi study is *iterative*, it allows experts to refine their value judgment in light of the overall progress of the group towards reaching consensus. An extensive overview of the Delphi method can be found in (Adler and Ziglio 1996). Limitations associated with workgroup elicitation methods include the risk of non-representativeness of expert panels, the need to achieve panel availability for the time required for a workgroup study, and risks associated with peer pressure and hidden agendas in methods where those ambiguities are not accounted explicitly.

This section reviewed methods for expert elicitation that can be used to support upstream systems architecting processes. Hybrid expert elicitation methods can be designed by combining the approaches reviewed above. This thesis presents a Delphi-Based Systems Architecting Framework (DB-SAF), for systems architecting under ambiguity in stakeholder objectives. The framework engineers the Delphi-method, and extends it up to tradespace exploration for effective identification and characterization of ambiguities. The DB-SAF framework is a structured process to inform effective strategies for systems architecting under ambiguity. However, a prior classification of ambiguity mitigation strategies is required to describe possible actions that system architects can take to mitigate ambiguities in their sytems. This discussion is done in Section 3.4.

## 3.4. Canonical Form Classification of Ambiguity Mitigation Strategies

Following the identification of sources of ambiguity, their classification, and a review of tools available for their elicitation, this section identifies ambiguity mitigation strategies and proposes a classification in canonical forms. We define canonical forms fundamental set of strategies that can be applied across a wide variety of disciplinary domains to mitigate ambiguity. Strategies have been identified by examining different use cases in the literature of engineering systems, engineering, political science, finance and economics, and management. Table 2 shows the results of this analysis.

Table 2 Canonical Forms of Ambiguity Mitigation Strategies

| ACTIONS | Engineering Systems | Engineering | Political Science | Finance & Economics | Management | Description |
|---|---|---|---|---|---|---|
| *Use Case* | *Mars Sample Return Campaign* | *Spacecraft Design* | *Risk Shielding Policy* | *Investment Management* | *Business Plan* | |
| ***Compromise*** | Trade-off Analysis | Multidisciplinary System Design Optimization [Agte 2010] | Policy Making | Capital Asset Pricing Model (CAPM) [Merton 1973] | SWOT Analysis [Hill 1997] | To achieve an optimal compromise decision based on currently available information. |
| ***Consensus*** | Expert Elicitation [EPA 2009] | Focus Groups [Krueger 2009] | Policy Delphi [Turoff 1970] | Specification of Investment Objectives and Constraints | Strategy Planning [Courtney 1997] | To achieve agreement of opinions among experts. |
| ***Buy Insurance*** | Robustness [Taguchi 1986] | Design Redundancy | Precautionary Principle [Harremoes 2001] | Hedging Strategies (i.e. Credit Default Swaps) | Contigency Planning [Goodstein 1992] | To minimize downside ambiguous risks with payment of an upfront cost. |
| ***Defer Actions*** | Flexibility in Engineering Systems [de Neufville 2006] | Conditional Planning (AI) [Hendler 1992] | Laissez Faire [Sapolsky 1990] | Financial Options [Black and Scholes 1973] | Discovery-Driven Planning [McGrath and MacMillan 1995] | To purchase the option to act at a later time. |
| ***Deterrence*** | Lock-in decisions | Standards | Litigation | Revelation of information [Scott 1993] | Entry Barriers [Dixit 1979] | To pose threats to adverse behaviors. |

Five fundamental actions to mitigate ambiguity are identified:

- **Compromise:** to achieve an optimal compromise decision based on currently available information. This equals to the determination of optimal compromises between contrasting needs, maximizing stakeholder group's value instead of individual stakeholders value.
- **Consensus:** to achieve agreement of opinions among experts. Consensus happens in presence of reducible ambiguities, where experts agree on definitions, assumptions and associated value on questions of interest.
- **Buy Insurance:** to minimize downside ambiguous risks with payment of an upfront cost. This equals to the concept of robustness in engineering design, and to policy robustness as discussed in this thesis.
- **Defer Actions:** to purchase the option to act at a later time. This equals to the embodiment of real options in engineering systems, where an upfront cost to hedge future uncertain risks.
- **Deterrence:** to pose threats to adverse behaviors. This equals to freezing certain requirements in the early stages of the design process, to avoid abrupt changes in future phases. As it might be seen, this action has adverse effects in many cases. Its use is foreseen in rare cases, where other mitigating actions fail in meeting their objectives.

The left-hand column of Table 2 shows the five canonical forms of ambiguity mitigation strategies (Compromise, Consensus, Buy Insurance, Defer Actions, Deterrence). The next five columns show the mapping of such strategies to the five disciplinary domains that have been investigated. The second row shows specific use cases that have been taken in consideration in the analysis. The analysis shows how canonical forms of ambiguity management strategies span a variety of disciplines while sharing fundamental insights. The question is then how to identify which set of actions to implement to mitigate ambiguities of interest. Section 3.5 answers this question, by presenting a descriptive framework for management of ambiguities.

## 3.5. Descriptive Systems Architecting Management Framework

The implementation of ambiguity management strategies need to be informed by analysis from the systems architect. This section presents a descriptive Systems Architecting Management Framework (SA-MF), that supports system architects in this process developing a descriptive Partially Observable Markov Model and describing a framework aimed at the identification of effective ambiguity management strategies from the canonical forms that have been identified in Section 3.4.

SA-MF is a descriptive approach to systems architecting under stakeholder ambiguity. In SA-MF, the systems architecting process is modeled as a set of <u>Actions</u> that the system architect implements to transition between system States. SA-MF goal is to identify an architecting Policy to maximize Rewards in form of stakeholder objectives of interest, while reducing reducible ambiguities, identifying irreducible ambiguities, and identifying Pareto-efficient system architectures of interest for further analysis by decision-makers. Rewards are unknown due to ambiguity in stakeholder objectives. The goal of SA-MF is to describe effective actions from canonical forms to implement as a next step in a systems architecting process. The goal of SA-MF is not to dynamically simulate management action outcomes, as it would be done in a control theory problem.

In SA-MF, actions are canonical forms of ambiguity management strategies as discussed in Section 3.4 (Table 2). Rewards are represented to contribution of the systems architecture to value as delivered to stakeholders (for instance, value delivered to scientists or policy-makers). States are represented by decision gates and stable forms of the architecture. Table 3 describes possible states, mapping to examples from the five use cases considered previously for canonical forms. Policies are system architecting strategies, representing the set of optimal state-action transitions across the lifecycle of the system. System architects can develop SA-MF models of their systems of interest, and reason through the model to identify ambiguities and ambiguity mitigation strategies. SA-MF has been developed using generic concepts, to allow its implementation in any engineering domain of interest. Figure 24 shows the general SA-MF model, where states are represented by nodes, actions are edges, and rewards are outcomes – represented by clouds, meaning ambiguity affecting their quantification *a priori* by the systems architect.

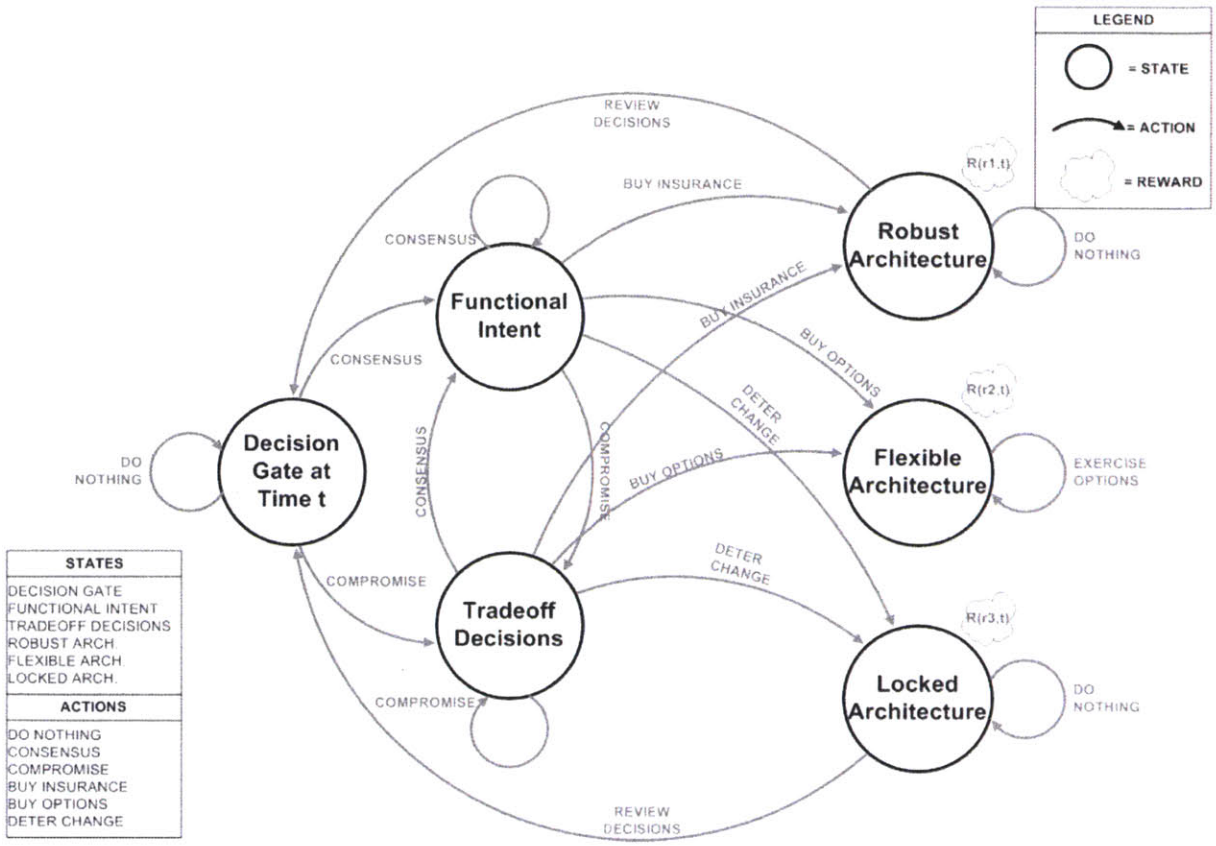



Figure 24 Descriptive Systems Architecting Management Framework (SA-MF)

Table 3 Systems Architecting Management Framework States

| STATES | Engineering Systems | Engineering | Political Science | Finance & Economics | Management | Description |
|---|---|---|---|---|---|---|
| *Use Case* | *Mars Sample Return Campaign* | *Spacecraft Design* | *Risk Shielding Policy* | *Investment Management* | *Business Plan* | |
| ***Decision Gate at Time t*** | Program Review | System Design Review [NASA 2007] | Congressional Voting | Performance Evaluation | Venture Capital Review | An approval event (often associated with a review meeting). [INCOSE 2007] |
| ***Functional Intent*** | Mission Architecture and Concept of Operations [NASA 2007] (3 element versus 2 element MSR campaign) | System Requirements Document | Safety Standards [Ashford 1998] | Investment Strategy | Mission Statement | The [set of] activities, operations and transformations that cause, create or contribute to performance [Crawley 2011] |
| ***Tradeoff Decisions*** | Sample Drilling Depth Decision [Aliakbargolkar 2012] (Balancing Science and Engineering Utility) | Power / Structure / AOCS Tradeoffs [Aliakbargolkar 2008] (i.e. Batteries Allocation) | Risk Analysis and Management [Morgan 1993] | Risk Tolerance [Grable 1999] | Time-to-Market vs Product Quality [Cohen 1996] | Decisions that involve losing one quality or aspect of something in return for gaining another quality or aspect. [Wikipedia 2011] |
| ***Robust Architecture*** | Separate Sample Caching / Fetching Rovers. [Aliakbargolkar 2012] (mitigate risk of loss of mission) | Hot / Cold Spare Components (i.e. redundant TT&C architecture) | Precautionary Bans [Harremoes 2001] | Portfolio Diversification [Markowitz 1991] | Business Contigency Plan | An architecture unsensitive to exogenous uncertainty. |
| ***Flexible Architecture*** | Extended Horizontal Mobility [Aliakbargolkar 2012] (i.e. operational flexibility) | Commercial Off The Shelf (COTS) Satellite Platform (i.e. Myriade [CNES 2011]) | Labels [Sapolsky 1990] | Hedging Strategies [Cusatis 2005] | Real Option Strategies [Luehrmann 1998] | An architecture capable of undergoing specified classes of changes with relative ease. [Moses 2002] |
| ***Locked Architecture*** | Retrieved Samples Mass [Aliakbargolkar 2012] (incentive on improving sample detection technologies) | RF Frequency Assignment Plans [ITU 2011] | Judicial Protection | Debt Securities [Dennis 2005] | Monopoly [Viscusi 2005] | An architecture locked to changes by exogenous agents. |

Consider the architecture of a Mars Sample Return (MSR) campaign as an application example. MSR is developed as a full case study in Chapter 4; readers can refer to this chapter for a description of specific details on the case study. We will consider here the development of SA-MF to this case.

Figure 25 shows the implementation of SA-MF to MSR. System architects can use the generic SA-MF framework and the list of canonical forms of ambiguity mitigation presented previously in Table 2 to develop a model specific to MSR. Program review is modeled as a decision gate to the definition of a mission architecture, linked to tradeoff decisions between science, engineering and programmatic objectives. Iterations between these states are identified and enabled by tradeoff studies and expert elicitation processes. Possible ambiguity mitigation strategies to implement are programmatic robustness (by splitting caching and fetching rovers), operational flexibility (by extending rover horizontal mobility), and lock-in decisions on the total mass of samples to retrieve on Earth. Review decisions are backward actions that refer to successive program reviews. By developing a SA-MF model of Mars Sample Return, system architects gains insights on possible options for mitigation strategies and develop a tool for reasoning through upstream systems architecting processes.

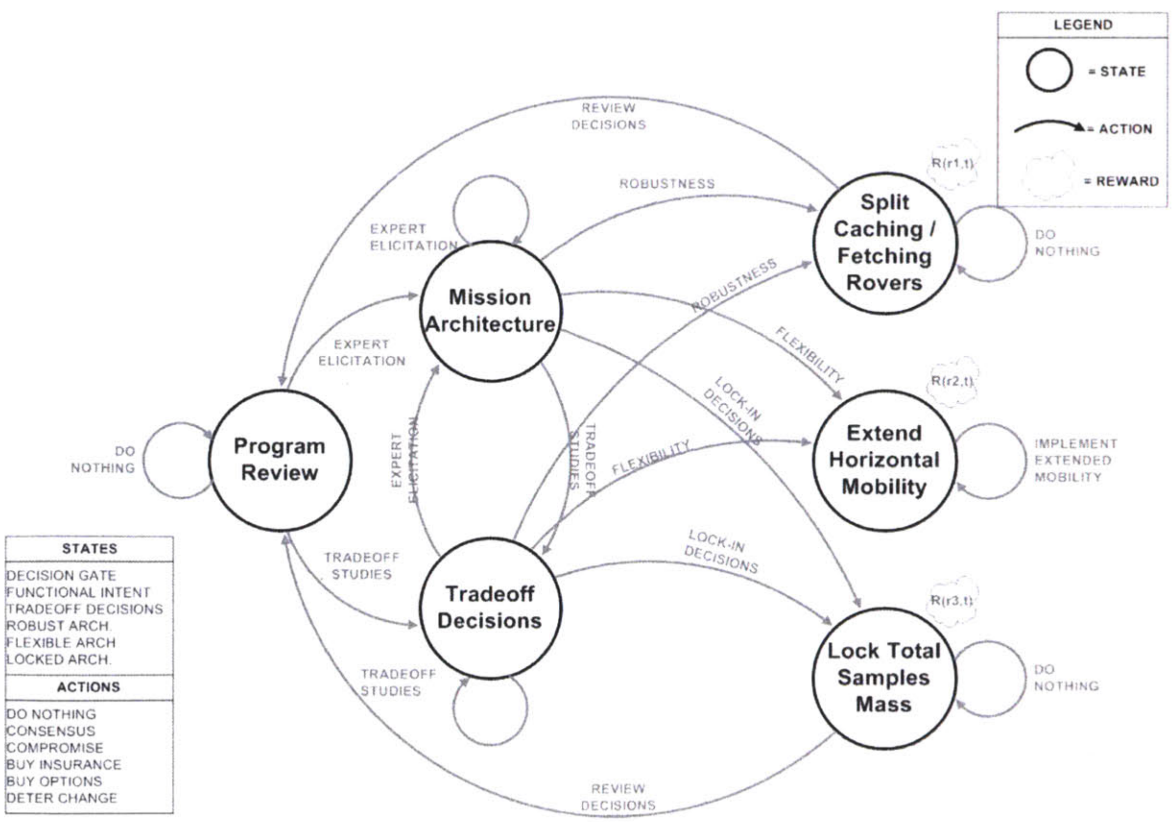



Figure 25 SA-MF Application to the Mars Sample Return Use Case

Selection of an ambiguity mitigation action is not a trivial task. Several options need to be considered. Furthermore, system architects need to account that decisions takes in the functional domain bear consequences in the formal domain in terms of performance, cost and risk trade-offs. A comprehensive system architecting analysis including ambiguity is therefore required to select mitigating actions as defined by SA-MF. The following section describes a tool that has been developed to this end, called the Delphi-Based Systems Architecting Framework (DB-SAF).

## 3.6. Delphi-Based Systems Architecting Framework

### 3.6.1. Overview

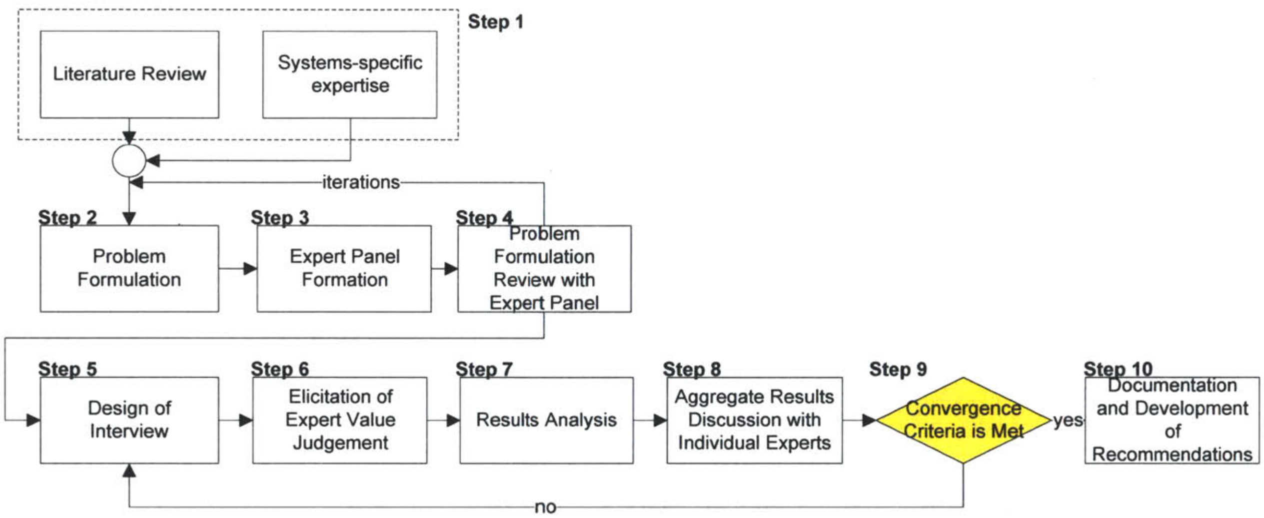



Figure 26 Proposed Systems Architecting Framework Overview

DB-SAF is a structured, iterative anonymous tool to inform ambiguity mitigation strategies as defined in SA-MF (discussed in Section 3.5) in systems architecting under stakeholder ambiguity. The framework is inspired by the Delphi method in policy-making (discussed in Section 3.3), and defines its systems architecting version in the context of formulation of new, unprecedented systems. Figure 26 provides an overview of DB-SAF. The framework integrates an engineered version of Delphi analysis Expert-Based Systems Architecting under ambiguity in stakeholder objectives, in conjunction with existing expert elicitation methods such as Score Cards and Multi Attribute Utility Analysis (MAUA) (Belton and Stewart 2002; Gibson, Scherer et al. 2007; Abbas 2010). DB-SAF consists in a structured process decomposed in the ten Steps. In the following description, we will refer to examples from the Mars Sample Return case study (Chapter 4) to contextualize the description.

### 3.6.2. Step 1 - Literature Review and Systems-Specific Expertise

The process starts from a preliminary *Literature Review* and the system architect's *System-Specific Expertise*. The purpose of the literature review is to gather existing information on the architecting problem of interest and inform *Problem Formulation* (*Step 2*). Documents of interest include previous point designs and architecting studies of the mission of interest and analog past missions, relevant academic literature, program-level documents and science-prioritization documents. For Mars missions, examples of point designs and architecting studies are the Mission Concept Studies developed in support of the latest Planetary Science Decadal Survey; for instance the *Mars 2018 MAX-C Caching Rover Assessment Study* (NASA 2010), the *MSR Lander Mission Study* (NASA 2010) and the *MSR Orbiter Mission Study* (NASA 2010). An example of program-level document is the *Planetary Science Decadal Survey* (NRC 2011), whereas examples of science-prioritization documents are Reports of the *Mars Exploration Program Analysis Group* (*MEPAG*) (NASA 2010).

### 3.6.3. Step 2 – Problem Formulation

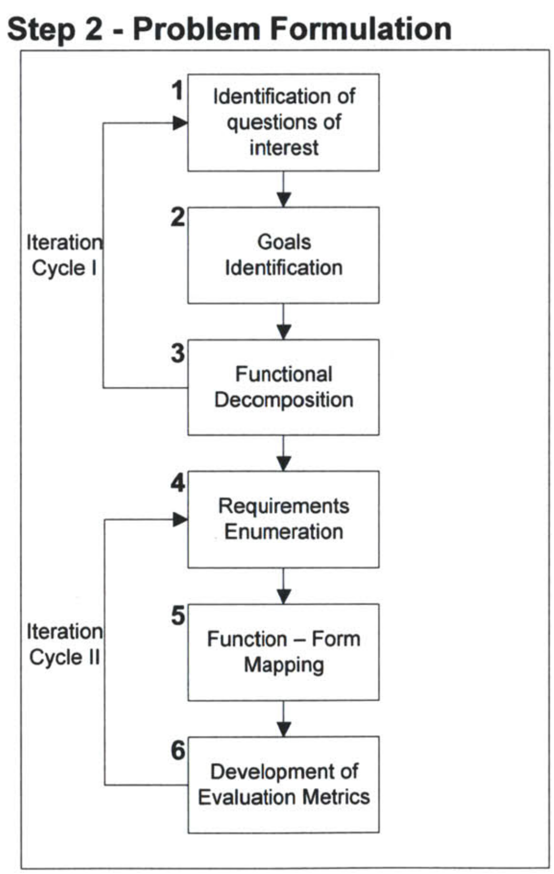



Figure 27 Step 2 - Problem Formulation

In Problem Formulation (Figure 27) the system architect defines the problem he/she wishes to address in support of the customer's project. The step consists in two sequential iterative cycles. Iterations are devised to refine each individual sub-steps, which definition benefits from the definition of the other sub-steps in the cycle.

### *3.6.3.1. Iterative Cycle 1*

1) *Identification of Beneficiaries Needs*

This sub-step identifies the needs of the beneficiaries of the system, formulating questions of interest to be addressed by his study. Examples of beneficiaries of a Mars Sample Return mission are astrobiologists and geologists that are wishing to further their science by retrieving data from Martian samples. Questions are formulated by direct interaction with the customer that is commissioning the study. Examples of questions of interest from the MSR campaign architecting example include: *What kind of sample types should MSR bring back to Earth to maximize scientific value while being implementable from an engineering and programmatic standpoint? What is the impact of the maximum drilling depth on the overall performance/cost/engineering complexity of the MSR campaign architecture?*

2) *Goals Identification*

System architects identify and characterize stakeholder goals to be fulfilled by the system. Stakeholder goals derive from beneficiaries' needs as well as additional socio-political considerations. Primary stakeholder goals can be identified with structured approaches such as *quantitative stakeholder analysis* (Cameron, Catanzaro et al. 2006) – this thesis does not cover stakeholder analysis and assumes that stakeholder goals have already been prioritized and documented. In addition to beneficiaries needs (such as the science goals defined by MEPAG for the MSR campaign (MEPAG 2008)), example additional goals that are set by stakeholders are policy robustness (i.e. ensuring the proposed mission is deemed acceptable by NASA decision-makers, Congress and other involved policy-makers), economic sustainability and education and outreach.

A non-exhaustive list of Stakeholder Goals for the Mars Sample Return campaign is presented in Table 4.

Table 4 Example Stakeholder Goals for the Mars Sample Return Campaign

| **Stakeholder Goals** |
|---|
| To Collect Samples of the Martian Surface |
| To Conduct In-situ Science on Mars |
| To Return Collected Samples to Earth |
| To Ensure collected samples comply with planetary protection requirements |

3) *Functional Decomposition*

Stakeholder Goals are decomposed into Functions that the system needs to perform in order to accomplish said goals. Functions are solution-neutral, as they do not depend on specific technologies or architectures; functions can be performed with different architectural options.

Functional decomposition can be performed at multiple levels of abstractions and hierarchy (i.e. decomposing functions, sub-functions, etc.). The level of abstraction depends on the type and purpose of study being conducted and on the time and resources available for analysis; as a general rule of thumb, campaign-level or program-level studies require functional decompositions to up to one or two levels.

The one-level functional decomposition for the Mars Sample Return campaign is shown in Table 5. A two-level functional decomposition is a further specification of functions at a lower level of abstraction. For instance, a two-level functional decomposition for MSR would specify the individual functions to be accomplished "*to entry the Martian atmosphere*" (Function 3 in Table 5).

Table 5 Functional Decomposition for the Mars Sample Return Campaign

| Functions | |
|---|---|
| 1 | To reach Low Earth Orbit |
| 2 | To transit between Low Earth Orbit and Low Mars Orbit |
| 3 | To entry Martian atmosphere |
| 4 | To descend and land on Martian surface |
| 5 | To drill Martian Surface and prepare Sample Caches for Fetching |
| 6 | To fetch Sample Caches |
| 7 | To bring Sample Caches to Earth Surface |

#### 3.6.3.2. Iterative Cycle 2

4) *Enumeration of Possible Sets of System Requirements*

System Requirements are quantitative specifications of the extent to which the architecture needs to be designed to meet its Stakeholder Goals. In this step, the system architect enumerates all the possible sets of System Requirements that the system could be designed for. Consideration of multiple set of requirements is desired for successive evaluation of the overall architecture and its value in terms of science performed, overall engineering complexity and cost (Steps 5-9). For instance, a set of possible requirements for the MSR campaign architecture is the following:

- *Sample Types Collected:* Sedimentary Material Only
- *Total Number of Samples Collected:* 20
- *Sample Size:* 1cm D x 5cm H (cylindrical sample)
- *Sample Depth:* up to 10m
- *Horizontal Radius:* up to 20km

The previous set of requirements is only one instance of all possible sets that could be conceived for a MSR campaign. Suppose for instance the system architect is interested in evaluating architectures that deliver from 10 to 40 samples of different type. Possible sample types are sedimentary materials, hydrothermally and low temperature altered rocks, igneous rocks, regolith, dust and atmospheric gas. Furthermore, the architect is interested in assessing architectures that retrieve samples of different size (small-sized, medium-sized and large-sized samples) at different depths: surface (2.5cm), 1-meter and 10-meter; he is also interested in exploring options where the baseline horizontal mobility is designed from 0 km (a lander configuration) to 50 km. Table 6 summarizes the set of possible options for each requirement; this type of tabular representation is usually defined as *structural morphological matrix* (Crawley 2008). A requirement set is defined by selecting one option per requirement. A full enumeration leads to 2304 possible requirement sets. While there are no compatibility constraints in the MSR case, it could be the case that not all possible sets are feasible. Constraints can be used to prune unfeasible requirement sets out of the tradespace and leave only feasible options for study.

Table 6 Structural Morphological Matrix of Possible Requirement Sets for the Mars Sample Return Campaign

| Requirements | Options | | | | Number of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Drilling System Maximum Reachable Depth | Surface (~2.5cm) | 1-meter | 10-meter | | 3 |
| Total Number of Samples Collected | 10 | 20 | 30 | 40 | 4 |
| Sample Size | Small (0.5cm D x 1.0cm H) | Medium (1.0cm D x 5.0cm H) | Large (5.0cm D x 15cm H) | | 3 |
| Horizontal Diversity (characteristic radius) | 5 km | 10 km | 25 km | 50 km | 4 |
| Collect Sedimentary Material Samples | Yes | No | | | 2 |
| Collect Hydrothermally & Low Temp. Altered Samples | Yes | No | | | 2 |
| Collect Igneous Rock Samples | Yes | No | | | 2 |
| Collect Regolith, Dust & Atm. Gas Samples | Yes | No | | | 2 |
| | | | | Total No# of Possible Requirement Sets | 2304 |

5) *Function-Form Mapping*

Functions defined in sub-step 3 (Functional Decomposition) can be mapped to corresponding alternative options of Form. This thesis adopts Crawley's definition of form as "*the physical/informational embodiment which exists, or has the potential to exist*" (Crawley 2008). For instance, Function 2 in Table 5 (*to transit between Low Earth Orbit and Low Mars Orbit*) can be performed with different elements of form, such as the upper stage of a launch vehicle (such as a Centaur upper stage (Dawson and Bowles 2004)), a dedicated NTO/$N_2H_4$ or LOX/$LH_2$ propulsion modules. Form options can be summarized in a structural morphological matrix analogously to what has been done in sub-step 4 for requirements. The structural morphological matrix that synthesizes form options for the Mars Sample Return Campaign is presented in Table 7. Each row represents possible options for each element of form. Evaluation of alternative options for an element of form is traditionally referred to as a trade study. An architecture is defined by selecting one option per element of form. A full enumeration renders 96 possible architectures. Similarly as in the case of requirement sets, constraints can be used to prune non-sense architectures out of the tradespace. While cost constraints could be included during enumeration, it is recommended not to include them at this stage as this precludes a sensitivity analysis of performance as a function of cost as shown in later stages of the approach.

Table 7 Structural Morphological Matrix of Alternative Forms for the Mars Sample Return Campaign

| Forms | Options | | | | No# of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Number of Elements | 1 ((Drill + Fetch + Return)) | 2 (Drill + (Fetch and Return)) | 2 ((Drill and Fetch) + Return) | 3 ((Drill) + (Fetch) + (Return)) | 4 |
| Mars Ascent Vehicle (MAV) Number of Stages | 1 | 2 | 3 | | 3 |
| Earth Return Vehicle (ERV) Number of Stages | 1 | 2 | | | 2 |
| Mars Ascent Vehicle (MAV) Propulsion Type | Solid | Storable NTO/N2H4 | | | 2 |
| Earth Return Vehicle (ERV) Platform Type | MAV only | MAV + Orbiter | | | 2 |
| Earth Return Vehicle (ERV) Propulsion Type | Storable NTO/N2H4 | | | | 1 |
| | | | | Total No# of Architectures | 96 |

6) *Development of Evaluation Metrics*

Evaluation metrics are required to assess the overall value of architectures. Metrics can be classified as *objective metrics* and *subjective metrics*.

*Objective metrics* are quantities that can be measured or estimated either by direct measurement, first-principle modeling, parametric modeling or analog estimates. Examples of objectives metrics are dry mass, design velocity, time and lifecycle cost.

*Subjective metrics* are quantitative measures of subjective judgments. Examples of subjective metrics are perceived technical risk, perceived engineering complexity and perceived delivered value to scientists. Subjective metrics are estimated either by heuristic rules defined by experts, or by structured methods. An example of heuristic rule is to associate a higher perceived technical risk to architectures that feature a higher number of development projects and/or a higher number of operations perceived as potentially "risky" by the system architect – such as for instance in-orbit refueling in a space transportation architecting study. In addition to heuristic rules, several structured methods exist to measure subjective metrics.

This thesis adopts two different structured methods for subjective metrics evaluation: score cards and multi-attribute utility theory. A selection of a structured methods depends on the characteristics of the problem at hand and types of property values to be assessed. Strenghts and limitations of these methods as identified by this thesis are discussed.

Before getting into this discussion, it is useful to make the distinction between *ordinal* and *cardinal* metrics that can be developed for systems architecting. Ordinal metrics are used provide a ranking between competing architectures. They are therefore metrics for relative ranking. Cardinal metrics, in turn, are absolute metrics for relative ranking. Cardinal metrics are possible when incremental units are constant and objective. As this is seldom the case in subjective value metrics, subjective metrics as defined in this thesis must be intended in an ordinal sense. Indifference analysis for the identification of Pareto-efficient architecture is still possible, in fact, with ordinal metrics.

*Score cards* is the first method we use for the development of subjective value metrics. Score cards consist in eliciting knowledge by asking experts to rate property variables of interest on a pre-defined ordinal Likert scale (Likert 1932). The level of resolution of the Likert scale is a choice of the system architect, where a trade-off is made between the amount of information available to make a judgment and the level of granularity allowed by the metric. In a human spaceflight case study, for instance, one could ask experts to assign a score to the value associated with time of flight seen as a health of proxy risk for a mission beyond Low Earth Orbit (as shown in the example in Table 8). The preliminary assumption is that lower time in orbit is better, as it exposes astronauts to less of a health risk due to solar and cosmic radiation. Experts can also be asked to provide motivations to back up their scores, which forms valuable documentation for traceability and credibility of the subjective value metric being developed.

Table 8 Score card example

| Likert Scale | 1 = very high health risk | 2 = high health risk | 3 = moderate health risk | 4 = low health risk | 5 = very low health risk |
|---|---|---|---|---|---|
| Time of Flight [yrs] (as proxy of health risk) | 0.5y | 1.0y | 1.5y | 2.0y | 2.5y |
| Assigned Value | 5 | 3 | 2 | 1 | 1 |
| Motivations | ISS experience | Based on current knowledge on adverse health risks due to long-term permanence of astronauts beyond Low Earth Orbit. This rating is based on current (2012) knowledge and technology available for radiation protection. | | | |

Similar questions could be asked for other property variables of interest. Let $\vec{P}\big|_E = \begin{bmatrix} P_1(\vec{x}) & P_2(\vec{x}) & \dots & P_P(\vec{x}) \end{bmatrix}\Big|_E$ be the vector of property variables assessed by expert E, with $\vec{x}$ being the input design vector that defines the requirement set. Score cards can then be integrated in a joint value metric as a weighted linear combination or other representative functions of interest. Weights can be either elicited by experts (as discussed in 3.6.6) or assumed by the systems architect. The main advantage of score cards lies in their simplicity, and general applicability to any types of property variables. In particular, they are useful in evaluating property values with no monetary equivalent. However, they have less of a rigorous mathematical foundation than utility theory (discussed below), and scores might prove being challenging to assign when no "anchor points" are available, i.e. reference points on which experts can base their judgment. Score cards have been used in the human spaceflight case study in Chapter 5.

*Utility theory* (Fishburn 1970) is a second approach to subjective evaluation. Utility theory comprises several approaches used in finance and econometrics to estimate perceived value – for instance of value that an investor associates to some capital investment. In recent years, utility theory has been applied to estimate value in engineering systems analysis problems (Ross and Hastings 2005). As detailed in Steps 5-6, the proposed framework makes use of a utility theory approach (Multi Attribute Utility Analysis – MAUA) to estimate the value delivered to scientists, engineers and to the program manager of a project. Table 9 summarizes the evaluation metrics that have been developed for the Mars Sample Return Campaign case study. Total technical risk is defined heuristically as the total number of development projects within an architecture.

Table 9 Evaluation metrics for the Mars Sample Return Campaign case study

| Objective metrics | Units | Subjective metrics | Units |
|---|---|---|---|
| Total Dry Mass | kg | Utility to Scientists | - |
| Total Wet Mass | kg | Utility to Engineers | - |
| Total Lifecycle Cost | FY15 M$ | | |

### 3.6.4. Step 3 - Expert Panel Formation

This step is concerned with the formation of the panel of experts to be involved in the study. In this thesis, the word "panel" refers to the aggregate of experts being involved in the study. However, it must be noted that experts do not meet during the decision-making process, as they interact by means of a moderator. Advantages and disadvantages of this approach have been explored through the retrospective validation case study in Chapter 6. Selecting experts is a critical step in the framework as the quality of the results is strongly dependent on the quality of the answers given by the expert panel as a whole. The architecting team in charge of the study identifies a first set of individuals to be involved. A larger set of study participants can be identified using "snowballing" sampling methods (Mason 1996), i.e. by asking existing participants to identify additional participants among their acquaintances. The process can be repeated until the architecting team is satisfied with the number of experts available for the study. The panel should be a good representative of the community of stakeholders interested in the mission, in order to represent all views and biases in an equal and fair manner.

(Rowe, Wright et al. 1991) identifies four key characteristics that define a "good" expert:

1. Knowledge and experience with the issues under investigation
2. Capacity and willingness to participate
3. Sufficient time to participate in the study
4. Effective communication skills

Once a panel of experts is formed, the architecting team will start the first round of interviews by reviewing the initial problem formulation, as outlined in Step 4.

### 3.6.5. Step 4 – Problem Formulation Review with Expert Panel

This step ensures the validity of the problem formulation developed in Step 2, improving the alignment of the study to the issues that are felt relevant by the expert panel and the stakeholders. Iterations are required to review the problem formulation until the architecting team reaches a satisfying conceptualization of the problem. A typical review list consists of the following items:

- Ensure the validity of modeling assumptions adopted in the framework;
- Ensure the validity and completeness of the list of questions to be addressed by the study (do the questions help to reduce ambiguity in the definition of a mission/campaign proposal?);
- Ensure the completeness of the needs perceived by the beneficiaries (do the needs represent all the relevant scientific questions of interest to the scientific community?);
- Ensure the completeness of the list of stakeholder goals and their biunivocal mapping to beneficiaries' needs (are there any redundant / untraced stakeholder goals? Are they required or is there any need that is not well represented in the current list?);
- Validate the minimum and maximum boundaries of interest for each requirement option that involves a quantitative assessment (such as the minimum and maximum number of retrieved samples to be considered in the study);
- Ensure the completeness of the list of system functions and their biunivocal mapping to stakeholder goals;
- Ensure the completeness of the list of requirements and their biunivocal mapping to system functions;
- Ensure the completeness of the list of options of form and their biunivocal mapping to the list of system functions;
- Ensure the validity of the evaluation metrics as developed.

Once the architecting team is satisfied with the revised problem formulation, it proceeds performing the elicitation of knowledge from the experts by designing a survey or interview (Step 5) and synthesizing their value judgment (Step 6).

### 3.6.6. Step 5 – Design of Interview

Designing the interview is a crucial step of the framework, as it involves careful consideration of the questions to be answered by the study as defined in Problem Formulation (Step 2), as well as considering behavioral aspects on choosing the best method to elicit knowledge from experts. This thesis presents a taxonomy of utility elicitation methods and toolkit of associated methodologies, based on score cards, utility theory and decision-making theory with particular focus on Multi Attribute Utility Analysis (MAUA).

#### Estimation of utility functions for attributes varying on continuous domains

Classical utility functions from utility theory are effective tools to represent value judgment for attributes varying on a continuous domain. Utility theory assumes that value can be represented by a normalized function of some attribute of interest. Figure 28 shows an example of single-attribute utility value of science value (for one given science interviewee) as a function of total number of samples retrieved on the surface of Mars.

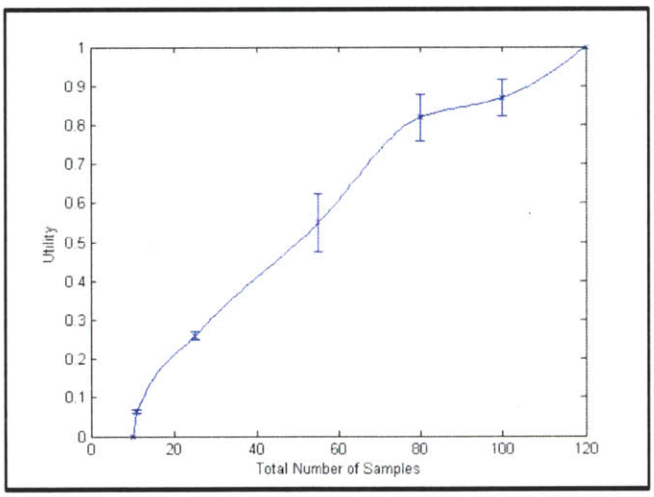



Figure 28 Example of single-attribute utility function

However, it is often the case that value is function of multiple attributes of interest, for which more articulated theories must be employed for value elicitation. MAUA is a decision analysis tool to represent an expert's value assessment as a function of multiple attributes. MAUA has been extensively surveyed in the literature (see (Wallenius, Dyer et al. 2008; Abbas 2010) for an extensive review), and therefore this thesis only covers the fundamentals and describes practical implementation techniques.

The two classical MAUA functions are the additive utility function and the multiplicative utility function.

The **additive utility function** assumes that aggregate utility (i.e. the total utility resulting by a particular combination of attributes) is a weighted sum of single-attribute utilities:

$$U(\vec{X}) = \sum_{i=1}^{N} k_i u_i(x_i) \qquad (1)$$

Where $\vec{X} = [x_i]$ is an attribute set and $k_i$ are scaling costants representing expert's priorities among attributes. Scaling constants in additive utility formulations are normalized to 1:

$$\sum_i k_i = 1 \qquad (2)$$

Nevertheless, it is often the case that aggregate utility is a non-linear combination of value associated with single attributes. The multiplicative utility function represents non-linear value expressions when preferential independence and utility independence (Keeney and Raiffa 1976) are satisfied. Those two conditions assume that preferences within an attribute set are independent of the values assumed by other attribute sets. For instance, they hold in a car purchasing situation where preferences over vehicle color do not depend on the particular type of vehicle being considered. It is possible to test the validity of those conditions for the problem of interest (Keeney and Raiffa 1976) and it is often the case that the problem can be formulated or refined in such a way to enter in this category of problems.

The mathematical expression of the **multiplicative utility function** is:

$$U(\vec{X}) = \frac{1}{K}\left(\prod\left[Kk_i u_i(x_i) + 1\right] - 1\right) \quad (3)$$

Where $k_i$ are multi-attribute scaling constants, $u_i(x_i)$ are single-attribute utility functions and K is a normalizing constant that scales $U(\vec{X})$ from 0 to 1. K can be calculated by numerical solution of the following equation:

$$1 + K = \prod(1 + Kk_i) \qquad (4)$$

Figure 29 shows an example 3D plot of multiplicative utility function depending on two attributes of interest.

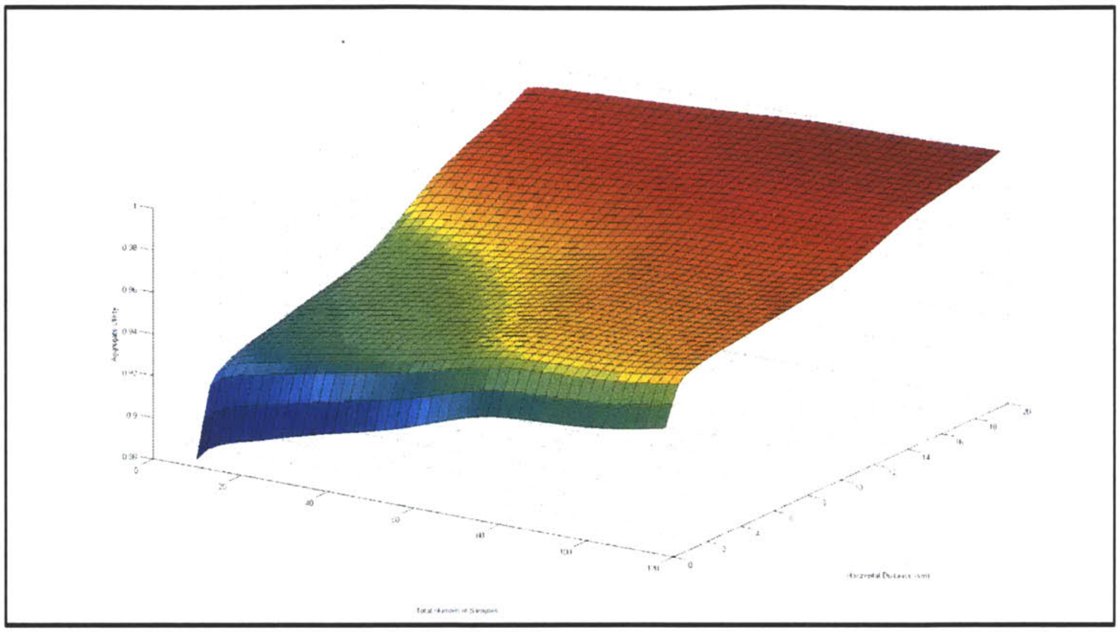


Figure 29 Example of Multi Attribute Utility Function

Methods used for estimation of single-attribute utility functions and weights depend on the type of attribute being assessed and on their mathematical expression - whether they are discrete values or span a continuous range of possible values. Utility function estimation methods are reviewed in (Keeney and Raiffa 1976). Two popular methods for utility elicitation are the Certainty Equivalent Probability (CEP) (Keeney and Raiffa 1976) method and the Lottery Equivalent Probability (LEP) (McCord and de Neufville 1986) method.

The CEP method requires the interviewee to estimate which probability p makes him/her indifferent between choosing a scenario where he is given an outcome $O_x$ with 100% probability, and a scenario where he either obtains an outcome $O_1$ with p probability or an outcome $O_2$ with (1-p) probability (Table 10). Once p is known, the utility associated with $O_x$ can be estimated as:

$$U(O_x) = pU(O_1) + (1-p)U(O_2) \quad (5)$$

The LEP method poses a similar question to the interviewee where he/she is asked to state his/her probability value for indifference between a scenario where he/she is given a 50% chance of receiving outcome $O_x$ and a 50% chance of receiving outcome $O_2$, and another scenario where he/she is given a probability p of obtaining $O_1$ and a (1-p) probability of obtaining outcome $O_2$ (Table 11). Utility in this case is estimated analogously as in equation (5). In LEP, probability values for p lie in between 0 and 0.5

in order to achieve consistent answers. CEP and LEP questions are usually "chained" such that successive questions make use of previously estimated information.

The chain of interviews probes experts for indifference questions between one outcome of unknown utility value (for instance the middle point of the range of interest) and two outcomes of known utility value. The chain is "primed" by using the extremal points of the range of interest: $O_{\min}$ for which utility value is arbitrarily set at 0 and $O_{\max}$ for which utility value is arbitrarily set as 1. Utility sampling is performed evenly across the range of possible values to obtain a set of single-attribute utility observations.

While a minimum recommended number of utility points to determine is around 5-7 to obtain a good estimate of utility across the range of interest, there is no maximum recommended number of interviews – this is usually set by practical limits such as the time available for the interview and the total number of questions to ask the expert in a questionnaire.

The final utility curve is obtained through least-square fitting of known utility models (such as the negative exponential utility function formulation (Keeney and Raiffa 1976)) or through piece-wise interpolation. The latter method is found to be more useful in engineering analysis, as "pre-canned" formulations were developed with specific purposes for different types of applications – such representing risk aversion in investment selection in finance and econometrics (Meyer 1987) – and do not account for typical situations encountered in the "real world" of engineering design practice. For instance, a common finding that emerged in this study is the existence of middle-range regions where utility functions exhibit flat plateaus. Such regions represent non-variations of utility in some ranges, for instance when engineering difficulty does not change significantly when designing a rover for 20km or 30km horizontal mobility. Piecewise cubic Hermite interpolation has been found significantly effective in correctly representing expert value judgments in this setting. CEP and LEP methods can be used concurrently to obtain redundant measurements and therefore estimate the uncertainty within the answers provided by the interviewee. The academic literature provides methods with which calibrate answers depending on the degree of consistency of experts and evaluate the quality of the overall assessment (Morgan and Henrion 1990).

Table 10 Certainty Equivalent Probability (CEP) method example

***What probability value p would make you indifferent in choosing between the following scenarios?***

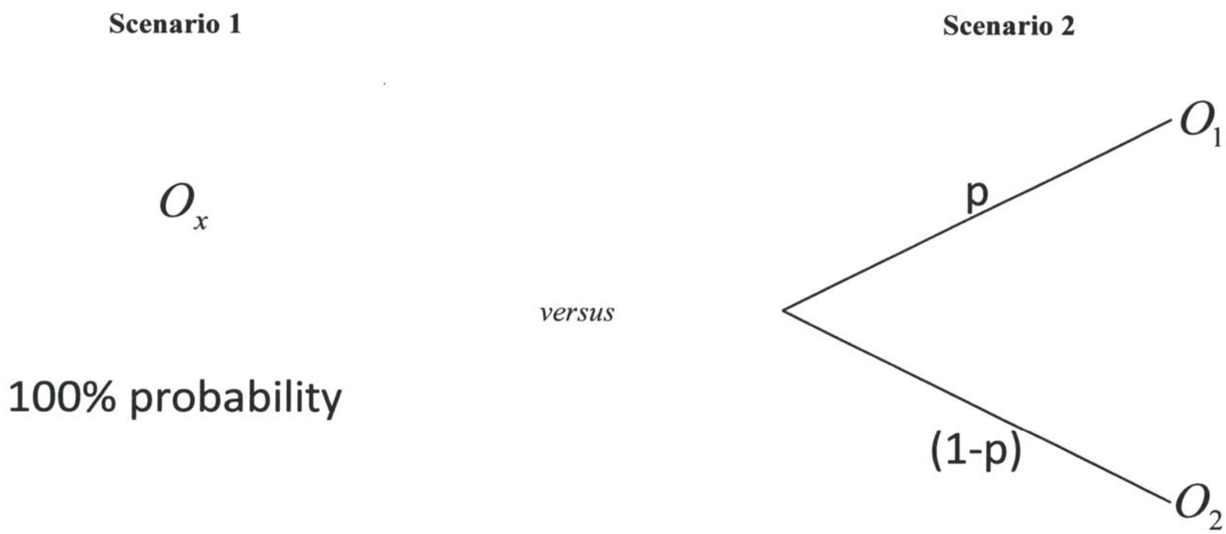
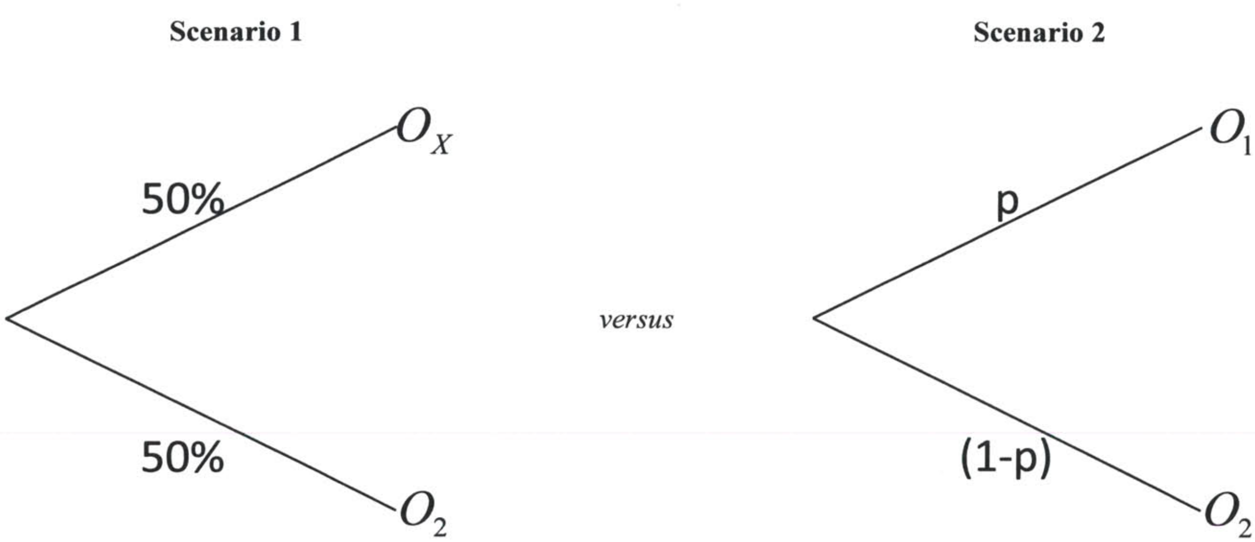



Table 11 Lottery Equivalent Probability (LEP) method example

***What probability value p would make you indifferent in choosing between the following scenarios?***



### *Weight Elicitation Procedures*

In both the additive and multiplicative formulations of multi-attribute utility, weights play the role of representing priorities across attributes as specified by experts. There are several weight elicitation procedures that have been proposed in the literature.

Three weight elicitation procedures that have been commonly used in engineering literature are the *ratio method* (Edwards 1977), the *swing method* (von Winterfeldt and Edwards 1986) and the *tradeoff method* (Keeney and Raiffa 1976).

The **ratio method** requires experts to rank attributes by importance. The least important attribute is given a weight of 10. The expert then specifies weights multiples of 10 for the other attributes, reflecting their relative importance.

The **swing method** presents experts an attribute set where each attribute is set at its worst value. The expert is then given a choice to select one attribute to "swing" to its optimal level, maximizing his utility. The first swing is assigned 100 points. Successively, the expert is asked to make a second swing and assign points to it, and iterate the procedure until complete evaluation of all weights.

The **tradeoff procedure** presents experts two scenarios differing for a pair of attributes (holding all other attributes at equal and constant values). The first scenario has the best value on the first attribute and the worst value on the second attribute. The second scenario presents a reversed situation. The expert is asked to select which alternative he/she prefers, therefore eliciting his ranking between associated weights. The actual value of the weights is determined by a CEP or LEP procedure by either worsening the value of the best attribute in the chosen scenario or improving the value of the worst attribute in the same chosen scenario. The indifference probability elicited determines the weights.

The ratio and swing methods are effective in determining weights for an additive multi-attribute utility formulation (where weights are successively normalized to 1). These methods are characterized by ease of implementation and understanding by interviewed experts. The tradeoff procedure, instead, is a more rigorous procedure for weight elicitation. The selection of a weight elicitation method on another depends on the type of attribute being probed and results from a balance in available time and number of questions presented in the interview and desired accuracy of results. Typically, a mix of methods is tested during the initial review of the problem formulation with experts, leading to a final method selection.

### Estimation of utility functions for attributes varying on discrete domains

The CEP and LEP methods discussed previously are not suitable methods for utility estimation if attributes vary on discrete domains such as when assessing the utility provided by the collection of samples of different types, varying between sedimentary materials, hydrothermally and low temperature altered rocks, igneous rocks and regolith – or a combination of those.

Discrete attributes are classified between *mutually excluding attributes* and *complementary attributes*. **Mutually excluding attributes** are defined as attributes which can take only one value among a range of possibilities. An example of mutually excluding attribute is the size of a sample of Martian soil. The sample can either be small, medium or large, but cannot be small and large at the same time. **Complementary attributes** are defined as attributes which can take more values among a range of possible options. An example of complementary attribute is the diversity of a sample portfolio; a MSR mission can be designed to sample only sedimentary materials, or a combination of sedimentary materials, regolith and igneous rocks.

Different methods for utility estimation are proposed in this thesis for utility functions that depend on mutually excluding attributes and complementary attributes.

### Estimation of utility functions for mutually excluding discrete attributes

Examples of mutually excluding discrete attributes abound in engineering applications: the size of a sample (small or large), the shape of a component (rectangular or cylindrical) and types of attitude control method (3 axis stabilized or spin stabilized) are all examples of attributes that span a discrete domain of possible choices. By necessity, utility in this case is defined by the interviewee relatively to a reference choice (which utility is normalized to one).

A modified version of the ratio procedure discussed for weight elicitation can be employed for utility estimation of mutually excluding discrete attributes. In the proposed procedure, the experts are asked to rank alternative values of the attribute of interest. The first-ranking (best) attribute is given 100 points. The interviewee is then asked to assign decreasing points – multiple of 10 – to the other alternatives. As a consistency check, a second round of interview can be conducted where now the last-ranking (worst) attribute is given 10 points. This time, the expert is asked to assign increasing points to the remaining alternatives. Successive normalization to the best-ranking alternative will yield utility values for the attribute of interest.

This proposed procedure features high ease of implementation and rapid understanding from interviewed experts; however, it is not as rigorous as what it could be achieved using a tradeoff procedure such as the one discussed in weight elicitation. Selection of a method over another will result from a balance of available time and complexity in the interview, and is left to the judgment of the architecting team implementing the proposed framework.

### Estimation of utility for complementary discrete attributes

Portfolio compositions are typical applications that can be described using complementary discrete attributes. For instance, a portfolio of sample types to be retrieved on the Martian surface can comprise different types of samples (NASA 2010):

- Sedimentary Materials
- Hydrothermally and Low Temperature Altered Rocks
- Igneous Rocks
- Regolith, Dust and Atmospheric Gas

A combined implementation of an additive utility formulation and CEP/LEP interviews for weight elicitation can be used to estimate utility associated with a complementary discrete attribute set. Associated utility equals:

$$U(\vec{X}) = \sum_i k_i u_i(x_i) \qquad (6)$$

Where $u_i(x_i)$ are binary single-attribute utility functions that assume value 0 if attribute option i is selected if selection is deemed beneficial by the expert and value 1 if attribute option i is not selected, if selection is deemed non beneficial. Utility values are reversed if selection is deemed as non-beneficial and non-selection as beneficial.

Normalized weights $k_i$ represent the relative importance of each attribute value selected in the attribute and are estimated through CEP/LEP interviews.

### 3.6.7. Step 6 – Elicitation of Expert Value Judgment

Elicitation of expert value judgment consists in the administration of the interview designed in Step 5 with each expert via individual face-to-face meetings, phone meetings or using a custom designed web tool. The interview is required to comply the requirements of a Delphi study that is, ensuring anonymity of participants of the study and verifying the expert complies with requirements discussed in Step 3 (Expert Panel Formation). Significant behavioral aspects emerged during the administration of value judgment interviews with experts involved in the MSR campaign case study.

The following list summarizes **ten lessons learnt** that derived from behavioral aspects emerged consistently during interviews:

1. **Ask the right question:** careful effort must be spent to tailor the interview to the background and personality of the interviewee. Different interview styles are recommended

depending on his/her background and bias deriving from varying research interests. The interviewer must clarify in the interview that results will be released in anonymous form (therefore reducing social pressure) and that the interviewee will have a chance to review results and change his mind in subsequent rounds of the process. For instance, while determining the value of increasing horizontal mobility for a rover system, one might want to ask a scientist what is the added science value of driving additional kilometers. If the question was addressed to an engineering audience, one would ask what is the perceived added penalty introduced in the system by extending the mobility range. While the interviewer should try to drive the expert in formulating accurate response, he/she must not look for double-digit precision answers as they both intimidate the expert and they do not add value to the quality of the results.

2. **Ask the question right:** Many engineers and scientists are used dealing with quantitative analysis on observable quantities. Some will refuse a priori the idea of attempting quantifying non-observable, subjective measurements such as value. For this reason, it is critical that the interviewer conducts a thorough literature review and it uses the proper terminology in formulating questions. While the same concepts can be expressed with different words having the same meaning, it is recommended that the interviewer adapts his terminology to what is commonly used in the organization in which the interview is being conducted. So for instance, while the words "campaign" and "program" can be synonyms in some contexts, this might not be the case in the organization of interest. Improper use of terminology may introduce unwanted biases or may let the interviewee not to understand questions, therefore reducing the quality of the final results.
3. **Set boundaries to insatiability:** Experts may face sometimes difficulty in setting boundaries for the attributes for the study. This is due to the fact that most of the times the subject of the investigation is unknown and highly exploratory – therefore experts face high degrees of uncertainty in defining their own value judgment. This is found to be true in particular among scientific communities. Science as a whole is a highly complex and exploratory endeavor; therefore it is hard (if not impossible) in certain instances to define boundaries of interest. Several scientists that were asked for the maximum number of samples they were willing to consider for a MSR campaign, answered that infinite was the correct answer ("*the more, the merrier*"). Although this answer may sometimes correspond to the actual truth, it is required to guide the expert towards setting a reasonable boundary to allow elicitation of value judgment. Setting of a boundary is required nevertheless to eventually specify a system requirement for the actual mission. The interviewer should facilitate this process by

proposing some number based on his expertise and preliminary literature review. The interviewer should attempt reaching an initial agreement with the interviewee. The answer being selected does not necessarily need to be the right one, as it will likely change during the course of the study in further iterations. As prescribed by Delphi guidelines and discussed in Step 8, the interviewer and interviewee have a chance to negotiate and attempt reaching consensus while analyzing aggregate data from each study iteration – researchers of the Delphi method proved that this approach yields eventually to the true result, or at the very least provides a reasonable approximation that reduces ambiguity from initial stages of the study (Rowe and Wright 1999).

4. **Ensure that answers are not biased by implicit tradeoffs:** The interviewer should not let the interviewee take the place of the model, that is, give answers based on implicit tradeoffs thus dampening the expert's actual preference. This is true in particular with interviewees involved in multidisciplinary aspects of a project. The interviewer should remind the interviewee to give answers that are based on his/her perspective only, since tradeoffs will be conducted successively by quantitative modeling and aggregation of opinions.
5. **Record the justifying rationale of each answer:** Recording rationale is critical to ensure credibility of the model to the customer and to conduct subsequent iterations of the study, where experts are asked to revise their answers in light of the aggregate of the answers given by the rest of the expert panel (as discussed in Step 8). If rationale is not recorded, the whole modeling effort will lose credibility to the eyes of both the experts and the customer. It is critical for the modeler to be able to understand the "physics" of the problem and to be able to justify every single aspect and implication of the results of his work.
6. **Avoid prejudices and perception of conflicts of interest:** The interviewer must make clear that his study will not compromise the position of the interviewee in the organization by all means, as answers are maintained anonymous at all times and shown in aggregate form only. If an interviewee is found to be uncooperative in contributing to the study, participation should not be forced. An effective contribution is provided only by mutual cooperation between the interviewer and interviewee.
7. **Minimize difficulty and help overcoming lack of confidence in exploring unknown areas of knowledge:** Experts might be hesitating providing answers in multidisciplinary areas of knowledge that include aspects that are not exactly their field of expertise. While careful selection of experts in Step 3 is designed to identify individuals with broad expertise in the problem being assessed, omniscience is seldom achieved by anyone. This is particularly true in modern engineering: arguably, no engineer is able to design a MSR

campaign by himself, hence showing the necessity of achieving group consensus. "Guesstimates" are often the only resource available, especially in situations or areas of knowledge that have never been probed in science or engineering. The iterative use of the Delphi method and the use group knowledge lead to more accurate answers than the ones expressed by individual alone.

8. **Recognize difficulty in expressing judgment on "extreme" situations:** Several interviewees showed difficulty in expressing judgment when asked to elicit preference among "extreme" situations. Such is the case when presenting an engineer to express an indifference probability between a scenario where he is asked to design a mission to carry an average number of samples with certainty (assume for instance 20 samples), and a scenario where there is a probability p where he will be asked to design to easier system requirements (assume 10 samples), or a (1-p) chance where he will be asked to design the system for an extremely challenging requirement, such as for 200 samples. One answer received by one of the interviewees in the MSR case study was: "*If there is even a slight chance that the adverse condition will occur, my career would be ruined, I am not willing to take that risk by all means and therefore I will set p at 100%*". The problem with this answer is that it will contradict other similar judgment statements, showing irrational behavior and invalidating the outcome of the study. This type of answers emerges when the interviewer does not explain properly the scope of the study. In the example before, it would have sufficed to the interviewer to explain that high risk aversion (such as the one demonstrated by the expert in question) can be expressed with a high probability value between 0 and 1 (but not equal to 0 or 1). Furthermore, the interviewer must stress to the expert that he will be able to review his answer in subsequent rounds in light of the aggregate judgment expressed by other experts – therefore providing more confidence in his value judgment.
9. **Minimize the bias induced by reverse engineering attempts:** Experts might try to give their answers based on their personal attempt of reverse engineering the methodologies used in the study, and providing answers that will most likely satisfy the scope of the investigation itself. For this reason, the interviewer should not disclose the "mechanics" of the methods being used to the interviewee during the course of the interview, as this could implicitly bias his/her answers. For instance, if the interviewee gives answers to CEP/LEP questionnaires based purely on expected value calculations, the interview will be invalidated in that biases and marginal preferences will not be represented in the resulting quantitative model.
10. **Validate and verify the results:** Follow up with the expert after each round for results review before data aggregation is very important to validate the overall modeling effort.

Review usually provides insight to both the interviewer and the expert himself, who might find the results useful for his own purposes as well (for instance, reusing them in other projects or similar proposals). A final review of the outcomes of the study with the expert panel is also recommended before releasing documentation and recommendations to management and decision makers (Step 10).

### 3.6.8. Step 7 – Results Analysis

After collecting data from experts, results are processed and incorporated into a systems architecting analysis model.

#### Objectives of Results Analysis

The **objectives** of the results analysis are:

1. **To identify a set of optimal requirements and architectures of interest** for further consideration by decision-makers by identifying the **set of Pareto-efficient architectures** among the feasible architectures within the design space and providing a first-order **scenario analysis**;
2. **To understand the impact of requirement options** in the overall performance of feasible architectures by performing a **multi-performance architectural analysis** of the design space;
3. **To understand the impact of architectural options** in the implementation of all possible sets of requirements for a mission or campaign by performing a **trade-off architectural analysis** in the design space.

**The framework presented in this thesis enhances systems architecting analysis by proposing a Delphi-based integrated framework to reduce ambiguity in the definition of objectives as elicited by stakeholders and supporting their negotiations.**

**The proposed Delphi-based integrated framework supports stakeholders in reaching consensus in the definition of objectives, when appropriate, and to identify areas of open debate. For instance, it allows scientists and engineers to reach consensus and effective compromises in the definition of overall scientific value of a mission or campaign.**

#### Mathematical definition of Pareto dominance and Pareto efficiency

In typical aerospace applications, architectures are evaluated by performance cost metrics (such as total dry mass of an architecture), total cost, and other quantitative metrics as developed in Problem Formulation (Step 2). In a Pareto efficient architecture, no metric can be improved without worsening performance along other metrics. In other words, Pareto-efficient architectures feature optimal metric trade-offs in the design space of feasible solutions. A rigorous definition of Pareto-efficiency and its relevancy to systems architecting and engineering design is better clarified by introducing the concept of **dominance** in design space exploration.

An architecture can be represented by a design vector $\vec{X} = [x_i]$, where the $x_i$'s represent the values for each option in the integrated architectural assessment matrix discussed in Problem Formulation (Step 2) and reported in Table 12. An objective vector $\vec{J}_j(\vec{X}) = \left[j_{ji}(\vec{X})\right]$ is associated to each architecture $A_j$ in the design space of feasible architectures $D = \{A_j\}$. It is assumed that all objectives $j_{ji}(\vec{X})$ in the objective vector are to be maximized. In this case, architecture $A_m$ is said to be **dominated** in a Pareto sense by architecture $A_n$ if $\vec{J}_n > \vec{J}_m$ <u>for all</u> pairs $(j_{mi}, j_{ni}) \in (\vec{J}_m, \vec{J}_n)$. In other words, a decision-maker is always better off selecting architecture $A_n$ over architecture $A_m$ as architecture $A_n$ always features superior performance with respect to $A_m$. On the other hand, architecture $A_n$ is said to be **non-dominated** in a Pareto sense by architecture $A_m$. Architecture $A_n$ is said to be Pareto-efficient if it results non-dominated with respect to <u>all</u> the others architectures within the feasible design space. The set of all Pareto-efficient architectures in the design space constitutes the so called **Pareto frontier**, or **set of Pareto-efficient architectures**.

Table 12 Integrated Architecture Assessment Matrix

| Requirements | Alternative values | | | | No# of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Drilling System Maximum Reachable Depth | Surface (~2.5cm) | 1-meter | 10-meter | | 3 |
| Total Number of Samples Collected | 10 | 20 | 30 | 40 | 4 |
| Sample Size | Small (0.5cm D x 1.0cm H) | Medium (1.0cm D x 5.0cm H) | Large (5.0cm D x 15cm H) | | 3 |
| Horizontal Diversity (characteristic radius) | 5 km | 10 km | 25 km | 50 km | 4 |
| Collect Sedimentary Material Samples | Yes | No | | | 2 |
| Collect Hydrothermally & Low Temp. Altered Samples | Yes | No | | | 2 |
| Collect Igneous Rock Samples | Yes | No | | | 2 |
| Collect Regolith, Dust & Atm. Gas Samples | Yes | No | | | 2 |
| | | | | **Total No# of Possible Requirement Sets** | **2304** |
| **Architectural Decisions** | **Architectural Options** | | | | **No# of Options** |
| | 1 | 2 | 3 | 4 | |
| Number of Elements | 1 ((Drill + Fetch + Return)) | 2 (Drill + (Fetch and Return)) | 2 ((Drill and Fetch) + Return) | 3 ((Drill) + (Fetch) + (Return)) | 4 |
| Mars Ascent Vehicle (MAV) Number of Stages | 1 | 2 | 3 | | 3 |
| Earth Return Vehicle (ERV) Number of Stages | 1 | 2 | | | 2 |
| Mars Ascent Vehicle (MAV) Propulsion Type | Solid | Storable NTO/N2H4 | | | 2 |
| Earth Return Vehicle (ERV) Platform Type | MAV only | MAV + Orbiter | | | 2 |
| Earth Return Vehicle (ERV) Propulsion Type | Storable NTO/N2H4 | | | | 1 |
| | | | | **Total No# of Architectures** | **96** |
| | | | | **Total No# of Integrated Architectures** | **221184** |

### Pareto analysis in design space exploration

Figure 30 provides an example of identification of Pareto efficient architectures in design space analysis. The figure shows a sample bi-dimensional tradespace where each blue dot represents a feasible architecture as evaluated by two objective metrics defined by system architects.

Assuming that maximization of both metrics is desired, it is possible to identify the **utopia point**, which is the ideal point where both objectives are at their maximum. The set of Pareto-efficient architectures (red dots in the figure) are the ones which tend towards the utopia point and exhibit efficient trade-offs between objectives.

In the notional example in the figure, Pareto-efficient architectures are options of interest to decision-makers, featuring optimal solutions at different levels of engineering and scientific satisfaction; architectures with high engineering scores (featuring ease of implementation) will most likely result into architectures of low scientific value. This situation could represent, for instance, a MSR campaign where the caching element is represented by a lander with a scoop payload that only retrieves 10 grams of dust samples to Earth. On the other hand, architectures with high value delivery to scientists will most likely result to increased engineering difficulty. In the 2D notional example presented in Figure 30, Pareto efficient architectures are those that for a constant level of one objective (for instance, utility to engineers) provide the maximum level of the other objective (such as utility to scientists).

**Pareto analysis allows the identification of combinations of interest of requirements and system architectures, to be considered for further decision-making and analysis.**

**Pareto analysis is an effective tool to facilitate the achievement of an optimal compromise between scientific ambitions, engineering requirements and program management constraints.**

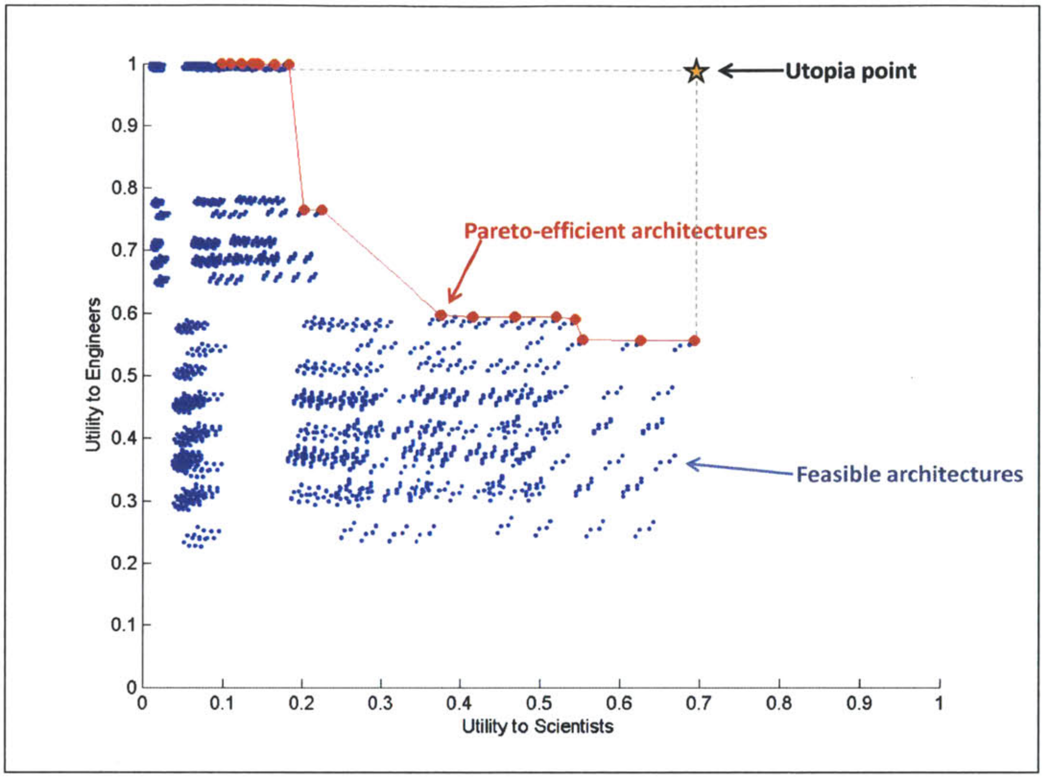



Figure 30 Design Space Example, Identification of Set of Pareto-efficient architectures

Design space exploration allows further elicitation of insights beyond simple Pareto analysis. It can be used to:

- Analyze the variation in performance/utility on system architectures due to change in requirements (multi-performance architectural analysis).
- Analyze the variation in performance/utility due to the implementation of different options to implement an architectural function of interest (trade-off analysis).

Design space exploration assumes consensus between homogeneous groups of stakeholders. This implies that, for instance, engineers reached consensus in the definition of engineering value (as represented by the "utility to engineers" function in the previous notional example) and that scientists reached consensus likewise in the definition of scientific value. Consensus implies that utility functions representing value in both group are representative of all opinions and therefore are "deterministic" (meaning that there is no uncertainty surrounding those functions). This condition is rarely verified in initial phases of a mission lifecycle. In reality, ambiguity in the definition of objective implies that utility functions are surrounded by uncertainty, and that the actual value judgments cannot be represented by univocal functions. Results analysis provides the means to reach optimal compromise between heterogeneous stakeholder groups – for instance, between the engineering and scientific communities. However, preliminary reaching of consensus is required within homogeneous groups of stakeholders. This is achieved through negotiation; the following step provides structured tools to guide those negotiations and progressively guide experts to agree towards an optimal definition of objectives.

### 3.6.9. Step 8 – Aggregate Results Discussion with Individual Experts

The Delphi method requires iterations to discuss results with individual experts. The goal is to guide experts revising their answers towards reaching consensus in the group. (Rowe 1991) describes the advantages of considering the aggregate response of a panel of experts towards reading the true answer being sought by the study: "*the so called 'theory of errors' assumes that the aggregate of a group will provide a judgment/forecast that is generally superior to that of most of the individuals within the group: when the range of individual estimates excludes the true answer (T), then the median (M) should be at least as close to the true answer as one half of the group, but when the range of estimates includes T, then M should be more accurate than more than half of the group. This indicates the advantage of taking a statistical aggregate of individual estimates*".

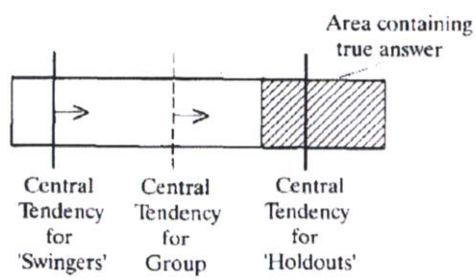



Figure 31 Theoretical change in group response over rounds (adapted from (Rowe, Wright et al. 1991))

Figure 31 exemplifies this concept showing the tendency of the group to move towards the true answer over iterations (defined "*rounds*" in Delphi jargon). Experts who gave outlier answers in the statistical aggregates are classified as *Holdouts* and *Swingers*. Holdouts are experts able to provide sound reasons justifying their outlier position. Swingers are experts showing less confidence on the answer and are willing to rely on group's knowledge by changing their answer even significantly. The overall result is that of driving the group towards the area containing the true answer over rounds.

Round iterations as prescribed by the Delphi have been by showing stakeholders aggregate *boxplot* charts. In descriptive statistics, boxplots describe groups of data through their *five-number summary*: the lowest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3) and largest observation (sample maximum) (Moore, McCabe et al. 2007). Figure 32 shows a boxplot example as referred to the probability density function of a normal population of data. In a boxplot, whiskers represent the lowest and largest observation. The edges of the box represent the lower and upper quartile (25% and 75% percentile), while the central bar represents the median.

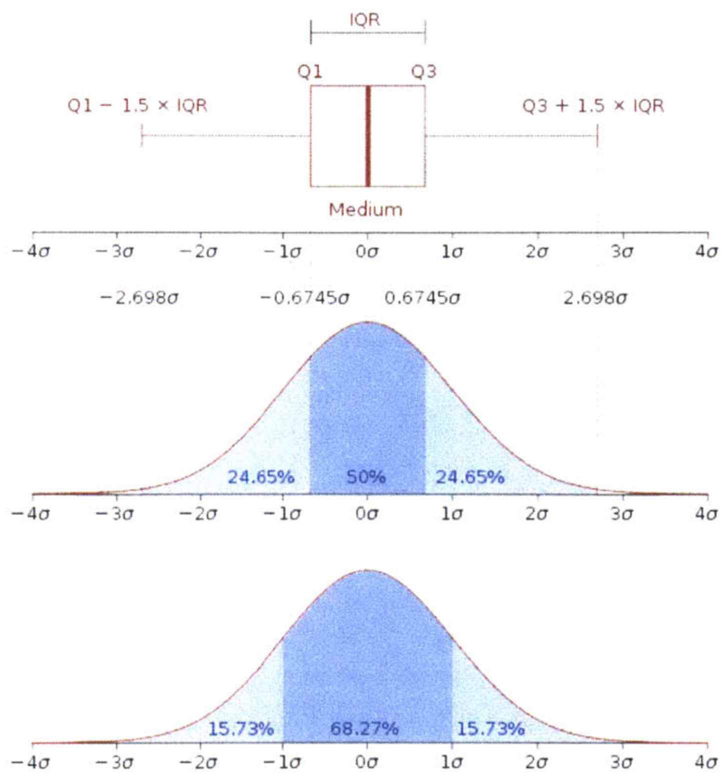



Figure 32 Boxplot example as referred to a probability density function of a normal population of data (adapted from (Wikipedia 2011))

After each round, experts are asked to review their answer in light of the aggregate answer of the group. Figure 33 shows an example of chart that used to facilitate discussion with experts, showing boxplots for each weight and utility function data derived during the Elicitation of Expert Value Judgment (Step 6). The pink dots represent the actual answer of the expert being interviewed. For each boxplot experts were asked to justify their answer and to either change it in light of the group's response, or keep it while providing justification in case the answer represents an outlier or lies outside of the edges of the box.

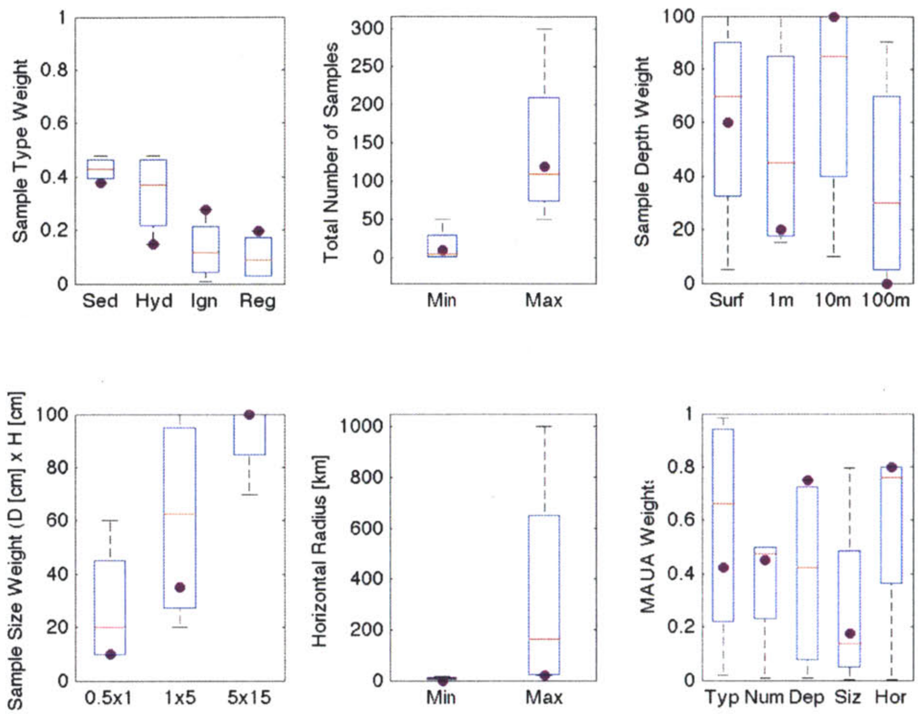



Figure 33 Example of boxplot chart for Results discussion iterations with experts

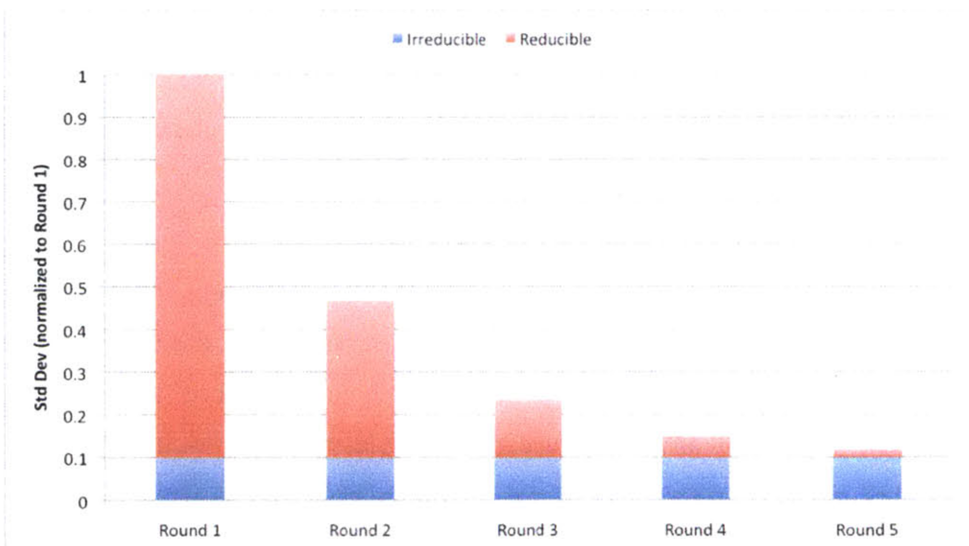



Figure 34 Reduction of ambiguity during Delphi round iterations

Overall, Delphi iterations reduce ambiguity that surrounds the definition of objectives for a system's architecture. Figure 34 shows this concept of progressive reduction of ambiguity during rounds of Delphi iterations. The figure represents the trend observed in the case studies conducted in this thesis, showing that most of the ambiguity is reduced during the first rounds of the Delphi exercise, while additional rounds serve the purpose of refining answers. This confirms previous empirical observations by researchers in social science (Rowe and Wright 1999). Furthermore, this thesis has found that when the subject of the investigation is mostly unknown (such as the case of the exploration of Mars), there exists an irreducible amount of ambiguity that cannot be resolved. This *irreducible ambiguity* can only be resolved after the mission being studied has actually been flow. For instance, it is impossible to know a priori that a given experimental design will lead with certainty to the proof of existence (or non existence) of life on Mars. Nevertheless, the goal of the system architect is fulfilled by Delphi iterations as reducible ambiguity has been eliminated, therefore ensuring that concept selection has been performed making the best use of the available rationale, therefore maximizing the expected value delivered to stakeholders and beneficiaries of the project.

An additional result of interest is to **assess the impact of identified ambiguities on the tradespace of feasible system architectures**. *Ambiguity Impact Analysis* can be done with several analytic and numeric methods, including:

- *Design of Experiments (DoE) and Sensitivity Analysis:* performing a full or factorial experiment, with ambiguous variables as factors (i.e. the property variables of the MAUA functions), and a number of percentile values as levels (such as the 0 [min] / 25 / 50 [median] / 75 / 100 [max] percentiles). Main effects and main interactions can be measured on a set of variables of interest, such as architectural utility values, mass, cost, and so forth. By this analysis, one can rank ambiguities by their overall impact on selected variables. This approach can be applied to compare individual system architectures, or to measure overall effect of ambiguities on the tradespace. We will demonstrate the application of this approach to this case.
- *Correlation Analysis:* In correlation analysis the goal is to identify correlations of the tradespace with ambiguous variables of interest. This is done by the examination of the tradespace with proxy metrics for variability induced by ambiguity. For instance, one could choose the standard deviation of subjective utility metrics associated with each architecture (where the spread is given by differences in opinions of individual experts in their respective panels). This approach is suitable for assessment of ambiguity impact on the tradespace as it does not require the definition of arbitrary weights, while allowing the analysis of a large dataset. We will use this as a second approach to confirm findings obtained with Design of Experiments.

- *Monte Carlo Analysis:* Monte Carlo is a popular approach for quantification of effects of multi-domain uncertainties. Its popularity is derived by the relative simplicity of implementation, and the widespread availability of computing capability required by this method. Monte Carlo approaches are also applicable to the analysis of ambiguities. In this setting, a Monte Carlo analysis implies the definition of stochastic value metrics, defined by assuming distribution shapes to fit ambiguous data of interest (such as normal or triangular distributions). Stochastic value metrics are used to evaluate the tradespace a large number of times, therefore deriving statistics of interest to assess variability induced by ambiguity on output metrics of interest. The assumption of a distribution is arbitrary in this context, as there is no firm rationale on how to choose a distribution over another. Monte Carlo is a valid choice for comparison of selected architectures. However, the large size of the tradespace involved (which in this example is of the order of $\sim 10^5$) prevents the use of a Monte Carlo approach.

### 3.6.10. Step 9 – Convergence Criteria

DB-SAF is stopped when a criterion for convergence is met. Typical convergence criteria are the achievement of a pre-defined number of iterations, the achievement of consensus and the stability of results when variations in answers between two rounds are less than a pre-specified tolerance criterion. The median or mean results are used at the end of the Delphi process. The standard deviation at the final iteration represents the variability induced by the estimated irreducible ambiguity.

### 3.6.11. Step 10 – Documentation and Development of Recommendations

Once convergence has been met, the results of the resulting design space exploration are documented and used for the development of recommendations to the customer.

## 3.7. Summary

The job of a systems architect is to transform a set of needs and goals into a systems architecture (Simmons 2008). Successful systems architecting is threatened by ambiguities in the definition of stakeholder needs and goals and the definition of a functional intent (i.e. upstream systems architecting processes). This chapter developed an ontological analysis that identified perceived needs, intended functions, function/need and form function mapping, formal and functional constraints as potential sources of ambiguity in systems architecting (Section 3.1). In Section 3.2, ambiguities are classified in reducible and irreducible ambiguities, defining the need of a set of strategies for their mitigation. Section 3.3 presented tools that are used in elicitation of perceived stakeholder needs and other upstream architecting processes, and discussed their vulnerability to ambiguities that have been identified. Following this analysis, Section 3.4 presented a set of canonical forms for systems architecting under ambiguous stakeholder objectives, integrated within a descriptive Systems Architecting Management Framework (SA-MF, Section 3.5). System architects can use SA-MF as a descriptive tool to reason through ambiguities in their systems architecting process of interest. SA-MF requires comprehensive analysis to inform the selection of an ambiguity mitigation action. The analysis is performed by the development of a Delphi-Based Systems Architecting Framework (DB-SAF) in Section 3.6. DB-SAF is a structured, iterative anonymous tool for systems architecting under stakeholder ambiguity. The chapter presents a step-by-step implementation description of DB-SAF, describing tools that are available to system architects to model their architecting problems of interest.

This chapter developed the theoretical background and the integrated framework for systems architecting under ambiguity in stakeholder objectives. The remainder of the thesis applies this framework to application case studies in Chapter 4 and Chapter 5, and describes a retrospective validation case study of the methodology in Chapter 6.

# Chapter 4 : Case Study 1 - Mars Sample Return Campaign

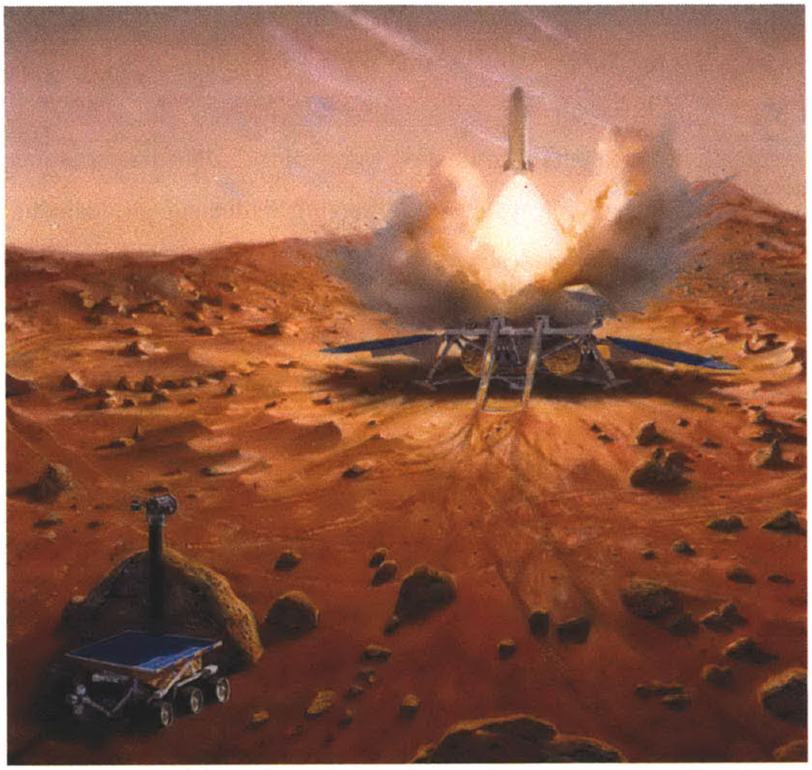


Figure 35 Mars Sample Return – Artist Concept (image credit: NASA)

## 4.1. Introduction

The first application case study of this thesis is an independent systems architecting study of the Mars Sample Return campaign. The study was formulated by the author between June 2011 and September 2011 at Caltech/NASA's Jet Propulsion Laboratory, and proceeded through December 2011 at MIT. The study involved expert panels with a total of 12 experts (senior engineers and scientists) from JPL, ESA, and academia. This chapter shows how the study successfully identifies ambiguities, proposes their classification and enables their reduction. Ambiguities are studied both in the definition of scientific objectives and engineering complexity for a MSR campaign, that is, the mapping between stakeholder needs and system functions. The framework integrates this requirement study with a conventional architectural assessment. The resulting design space exploration identifies Pareto efficient at different levels of cost and performance, with optimal compromises between science and engineering requirements. A benchmark against the existing 3-element campaign baseline as presented in recent Mission Concept Studies (NASA 2010) provides validation to the study.

## 4.2. Motivations and Context

Mars Sample Return (MSR) has been the holy grail of planetary science for many decades. Scientists have advocated a sample return mission to Mars for the past thirty years (NRC 2011). Nevertheless, MSR is still being studied in its formulation phase, trying to match the ambitious goal of returning samples from the Martian surface with the more terrestrial requirement of meeting the budget. Between March and April 2010, NASA published three Mission Concept Studies to support its Planetary Decadal Survey and propose a three-element architecture for a MSR campaign. Although being a mission of high scientific value and despite the efforts in spreading cost and technical risk in three mission elements, the MSR campaign still faces the challenge to reconcile its goals with available means. The Decadal Survey committee noted: "<...> *The highest priority large mission for the decade 2013-2022 is the Mars Astrobiology Explorer-Cacher (MAX-C), which will begin a three-mission NASA-ESA Mars Sample Return campaign extending into the decade beyond 2022. At an estimated cost of $3.5 billion as currently designed, however, MAX-C would take up a disproportionate share of the NASA's planetary budget.* <...> *The committee recommends that NASA fly MAX-C in the decade 2013-2022, but only if it can be conducted for a cost to NASA of no more than approximately $2.5 billion FY2015. If a cost of no more than about $2.5 billion FY2015 cannot be verified, the mission (and the subsequent elements of Mars Sample Return) should be deferred until a subsequent decade or cancelled.*" (NRC 2011).

Ambiguity in the definition of objectives for MSR stems from difficulty of compromise between science and engineering requirements, and from lack of consensus within both communities. Programmatic constraints are considered, such as cost caps, representing the challenge faced by program management in meeting ambitious objectives defined by scientists and technical boundaries defined by engineers under given cost caps.

Scientists involved in planning have different views on how a particular objective should be defined, such as how many samples collect from Mars to achieve a set of scientific goals. A clear example that has been identified in the study is the difference in value judgment between astrobiologists and geologists in the evaluation of alternative sets of requirements for the campaign. Figure 36 shows an example of science utility associated with different sample depths, as seen by two different stakeholders.

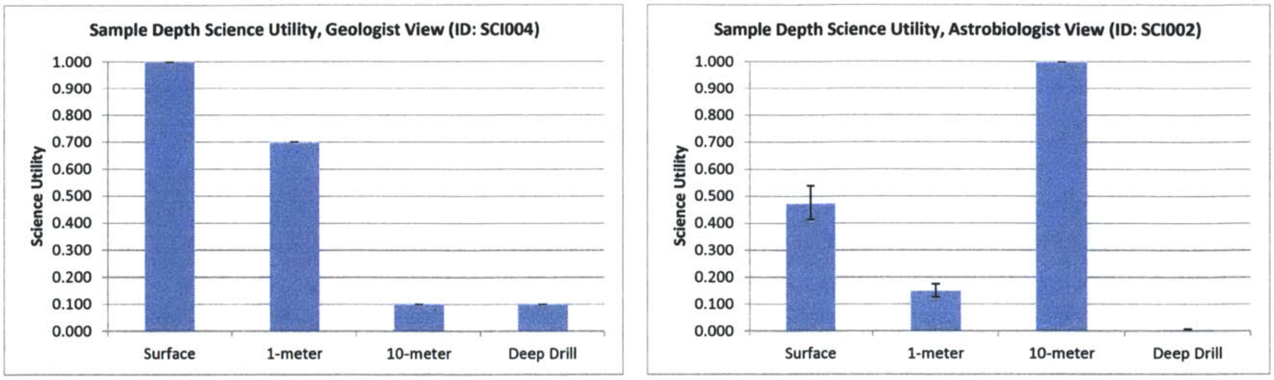



Figure 36 Science Utility associated with different Sample Depths as seen by different Views

In this example, experts were asked for their value judgment as a function of different attributes of interest. Value judgments were successively codified in utility functions. Sample depth could vary between surface drilling (2.5cm depth), 1-meter drilling, 10-meter drilling and deep drill (100m). Results were normalized to the maximum utility value for each set. The results showed that geologists were mostly interested in surface samples: 2.5cm in depth allows the collection of samples that have not been altered significantly by atmospheric processes (*unweathered samples* (Gooding, Arvidson et al. 1992)) while providing relevant information on the geologic processes that shaped the Martian surface. Deeper sample collections are deemed less valuable as their vertical distribution history is harder to keep during coring operations, rendering science hypothesis formulation and testing harder and less reliable. On the other side of the spectrum, astrobiologists indicated 10 meters as their most interesting sample depth, having higher likelihood of finding signs of life at those depths. Several analog examples can be identified in the data that has been collected for the study presented in this thesis.

**This case study investigates the impact of such diversity in opinion on simultaneous consideration of system requirements definition and systems architecture definition in terms of performance, on cost and risk metrics. Recommendations are eventually made on the selection of the system architecture to be implemented.**

## 4.3. Specific Objectives

This case study identifies, classifies and reduces ambiguities with emphasis on science value and engineering complexity as perceived subjective value metrics. The analysis uses multi-attribute utility theory as a formal means for expert elicitation. The specific goals of the analysis are the following:

- Characterize and identify reducible and irreducible ambiguities in the definition of a Mars Sample Return campaign architecture. The debate on scientific value and compromises with engineering complexity is analyzed and discussed;
- Enumerate possible requirements sets for a Mars Sample Return campaign, evaluating requirement sets with subjective value functions obtained with utility interviews;
- Identify requirement sets of interest for further analysis by system architects, and integrate them with a technical and programmatic analysis of system architectures, identifying alternative architectures and classifying them by cost using a Rough Order of Magnitude (ROM) mass-based cost metric.
- Identify architectures of interest for further consideration by decision-makers.

## 4.4. Application of the Framework

### 4.4.1. Step 1 – Literature Review and Systems-Specific Expertise

A literature review concerning the Mars Sample Return campaign has been conducted to inform the present study. The description of this review is out of the scope of this thesis; a review on the evolution of the Mars Sample Return campaign is provided by (Mattingly, Matousek et al. 2004). MEPAG reports are comprehensive accounts on current thinking for a Mars Sample Return mission. The MEPAG report or science priorities for a MSR mission is of particular interest to this thesis (MEPAG 2008). Mission concept studies from 2010 describe the three-element architecture of MSR developed by the Jet Propulsion Laboratory (NASA 2010; NASA 2010; NASA 2010; NASA 2010).

### 4.4.2. Step 2 – Problem Formulation

#### *4.4.2.1. Identification of questions of interest*

Through discussions with MSR management, experts and survey of the literature, eight questions emerged for research:

1. Does the current MSR architecture provide an efficient compromise between desired science returns and engineering complexity? (i.e. how far is it from ideal Pareto efficiency?)

2. What other Pareto-efficient MSR architectures could be devised for different levels of total cost?
3. What sample portfolio should MSR be designed for to maximize scientific returns?
4. What sample size should MSR be designed for optimal tradeoff between scientific returns and engineering complexity?
5. Is it worthwhile for MSR to accept the risk and invest in technology to retrieve samples beyond surface drilling (i.e. > 2.5cm)?
6. Is it worthwhile for MSR to accept the risk of extending horizontal mobility for distributed sample caching and in-situ science investigations?

#### *4.4.2.2. Goals identification*

As shown in the methodological discussion in Section Two, Table 13 presents campaign goals that have been identified for MSR.

Table 13 Example Stakeholder Goals for the Mars Sample Return Campaign

| **Stakeholder Goals** |
|---|
| To Collect Samples of the Martian Surface |
| To Conduct In-situ Science on Mars |
| To Return Collected Samples to Earth |
| To Ensure collected samples comply with planetary protection requirements |

#### *4.4.2.3. Functional decomposition*

The MSR architecture has been decomposed in functions derived from stakeholder goals (Table 14); the study recognized areas of interest for design space exploration within the functions regarding operations on the Martian surface and the transportation infrastructure beyond Trans Mars Injection (TMI). The study did not consider transportation options where an Earth Departure Stage was developed in addition to the upper stage of the launch vehicle. As the development of launch infrastructure is a given for a flight project and since most planetary missions can be performed with existing capabilities, this study assumed that existing launch capability would be used. Furthermore, the study considered an MSL-analog architecture for Entry, Descent and Landing; it considers the use of an Aeroshell and Sky Crane – derived landing system (NASA 2010).

Table 14 Functional decomposition for the MSR campaign architecture

| Functions | Included in Design Space Exploration? |
|---|---|
| To reach Low Earth Orbit | No |
| To transit between Low Earth Orbit and Low Mars Orbit | No |
| To entry the Martian atmosphere | No |
| To descend and land on Martian surface | No |
| To drill Martian Surface and prepare Sample Caches for Fetching | **Yes** |
| To Fetch Sample Caches | **Yes** |
| To Bring Sample Caches to Low Mars Orbit | **Yes** |
| To transit between Low Mars Orbit and Low Earth Orbit | **Yes** |
| To re-enter Earth atmosphere | **Yes** |

#### *4.4.2.4. Requirements Enumeration*

Table 15 Requirements identification and enumeration for the MSR campaign

| Requirements | Options | | | | Number of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Drilling System Maximum Reachable Depth | Surface (~2.5cm) | 1-meter | 10-meter | | 3 |
| Total Number of Samples Collected | 10 | 20 | 30 | 40 | 4 |
| Sample Size | Small (0.5cm D x 1.0cm H) | Medium (1.0cm D x 5.0cm H) | Large (5.0cm D x 15cm H) | | 3 |
| Horizontal Diversity (characteristic radius) | 5 km | 10 km | 25 km | 50 km | 4 |
| Collect Sedimentary Material Samples | Yes | No | | | 2 |
| Collect Hydrothermally & Low Temp. Altered Samples | Yes | No | | | 2 |
| Collect Igneous Rock Samples | Yes | No | | | 2 |
| Collect Regolith, Dust & Atm. Gas Samples | Yes | No | | | 2 |
| | | | | **Total Number of Possible Requirement Sets** | **2304** |

Table 15 shows the identification of requirements and enumeration of requirement options for the MSR campaign. The study focused in the investigation of requirements in the following areas:

*Sample Types Collected:* The composition of the portfolio of samples being collected is important to allow scientists to answer science questions of interest.

Following the literature review in Step 1 (with particular reference to science priorities identified by MEPAG (MEPAG 2008)), samples have been grouped in the following categories of interest:

- Sedimentary Materials
- Hydrothermally & Low Temperature Altered Rocks
- Igneous Rocks
- Regolith, Dust and Atmospheric Gas

In this study the collection of polar ices has been neglected as this type of sample entails particular challenges in terms of sample collection, sample preservation and planetary collection (being thermal control one of the most technical challenges), and it is not foreseen by the majority of experts as a sample type that will most likely be collected in a MSR campaign in the near future[1]. However, as this study is meant as a "proof of concept" and since all major relevant sample types are collected, this assumption is deemed appropriate for the type of analysis being conducted. In Table 15, different sample portfolios can be represented by selecting different combinations of Yes/No options for each sample type in the portfolio.

*Total Number of Samples:* different numbers of samples to be retrieved by MSR were investigated in the study. Most scientific experts expressed an ideal desire of retrieving infinite amount of samples to carry their investigation (see further discussion in Step 6). However, as naturally expected a number of samples to be retrieved must be determined to provide a requirement to design and perform a preliminary sizing of the architecture. The concept of *relevant samples* emerged during discussion with experts. Not all samples collected are relevant to answer specific questions of interest. Uncertainty in sample relevancy is hedged in the current MSR architecture by having the option of *selecting* samples during surface exploration. Nevertheless, this will not provide definite guarantee of relevancy of samples, which can only be proved by actual analysis on Earth. This study assumes that only 30% of collected samples are relevant for the purposes of expert value judgment elicitation. The study further assumes that the architecture retrieves the same amount of samples for each sample type within the portfolio. As a result of these assumptions, an MSR architecture designed to collect a total number of 100 samples of four different types will be expected to retrieve 25 samples per each sample type category. Of those 25, only 7 or 8 samples will be expected to be relevant to answer science questions of interest.

[1] Source: private conversations with JPL engineers

*Sample Depth:* the study investigated four different orders of magnitudes for sample depth to be considered as design reference for sizing of drilling payload and development of a concept of operations for sample coring and retrieval. The study investigated the following four sample depths:

- Surface (2.5cm) – the 2.5cm value has been selected to reflect the value being used in the current MSR baseline. 2.5cm allow retrieval of unweathered samples, i.e. samples that were not modified by surface atmospheric processes;
- 1-meter
- 10-meter
- Deep Drill (100-meter)

*Sample Size:* the study assumes collection of cylindrical samples of equal volume for each sample type in the portfolio. Three sample sizes were considered for investigation:

- Small (0.5cm D x 1.0cm H)
- Medium (1.0cm D x 5.0cm H)
- Large (5.0cm D x 15.0cm H)

*Horizontal Diversity:* Implementation of mobility in the MSR architecture allows systems to explore areas for in-situ science and enhanced capability of selecting samples for caching. A characteristic design radius to which the mobility system needs to be designed represents horizontal mobility. Options explored include mobility for 5km, 10km, 25km and 50km. Lander options (0km horizontal mobility) were initially considered for study and subsequently removed from the design space as discussion with science experts revealed a marked preference for mobility. With current landing site selection criteria in fact, engineers usually select flat regions for landing safety purposes. However, regions of interest to scientists are hills and terrains featuring geologic diversity, therefore eliciting the need of moving the caching system from its landing site to reach areas of high likelihood to have relevant samples for caching and retrieval.

#### *4.4.2.5. Function-Form Mapping*

Table 16 Function-form mapping

| Functions | Forms |
|---|---|
| To drill Martian Surface and prepare Sample Caches for Fetching | Drilling and Caching Rover |
| To Fetch Sample Caches | Fetch Rover |
| To Bring Sample Caches to Low Mars Orbit | Mars Ascent Vehicle |
| To transit between Low Mars Orbit and Low Earth Orbit | Mars Ascent Vehicle (MAV) or<br>Earth Return Vehicle (ERV) |
| To re-enter Earth atmosphere | Mars Ascent Vehicle (MAV) or<br>Earth Return Vehicle (ERV) |

Table 16 shows the mapping between functions and elements of form as intended in this study. Options are presented in Table 17 for each form. In this table, the number of elements refers to the partitioning of functions across different flight missions. Functions are:

- *Drill*: to retrieve samples from the Martian surface by drilling and to prepare them for return by caching;
- *Fetch*: to retrieve a sample cache on the Martian terrain and move it to the Return system;
- *Return*: to return samples from the Martian surface to Earth.

The "*Return*" function can be further partitioned in two options: either samples are returned via a combination of a Mars Ascent Vehicle (MAV) and an Earth Return Vehicle (ERV) (i.e. an Orbiter on Low Mars Orbit), or a MAV is designed to bring samples directly from Mars surface to Earth. Both the MAV and ERV can be conceived with a different number of stages; typically, one would consider between 1-3 stages for a MAV and between 1-2 stages for an ERV given the nominal delta V involved in their trajectory design. As a rule of thumb, one would expect that a 3 stage MAV would be required for direct sample retrieval (where the third stage would serve mainly for Trans Earth injection); a 2-stage ERV in a MAV+ERV scenario would serve the purpose of reducing the overall mass of the mission (the extent of said gain to be assessed by the architecting model), albeit at the additional technical and operational risk of adding staging operations to the MAV. Two propulsion options are assessed for the MAV (Solid propellant vs $NTO/N_2H_4$), whereas only one propulsion option is assumed for the ERV – although featuring higher specific impulse, $LOX/LH_2$ stages are not suitable in an MSR scenario due to out gassing constraints on mission lifetime, rendering this option unattractive due to long cruise times required to reach Mars and do the mission.

Table 17 Enumeration of options for elements of Form

| Forms | Options | | | | No# of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Number of Elements | 1 ((Drill + Fetch + Return)) | 2 (Drill + (Fetch and Return)) | 2 ((Drill and Fetch) + Return) | 3 ((Drill) + (Fetch) + (Return)) | 4 |
| Mars Ascent Vehicle (MAV) Number of Stages | 1 | 2 | 3 | | 3 |
| Earth Return Vehicle (ERV) Number of Stages | 1 | 2 | | | 2 |
| Mars Ascent Vehicle (MAV) Propulsion Type | Solid | Storable NTO/N2H4 | | | 2 |
| Earth Return Vehicle (ERV) Platform Type | MAV only | MAV + Orbiter | | | 2 |
| Earth Return Vehicle (ERV) Propulsion Type | Storable NTO/N2H4 | | | | 1 |
| | | | Total No# of Architectures | | 96 |

The resulting design space exploration model (Table 18) combines requirements and architecture enumeration rendering a total of 221,184 possible architectures.

As discussed in Section Two, the quantitative model identifies feasible architectures within the domain of possible combinations by applying technical and logical constraints. The following constraints have been applied to the model:

- Maximum total campaign cost = \$10B[2]
- Maximum total campaign dry mass = 20mt[3]
- Maximum allowable payload diameter = 4.5m
- MAV height < 4.0m
- ERV height < 4.0m

[2] Although in Section Two we recommended not to include cost constraints, an upper limit has been set in this case after a first analysis of results, to improve visualization on the region of interest of the design space (thus eliminating architectures with a large number of large samples) and non-convenient architectural implementations – such as 1-stage MAVs returning samples to Earth directly).

[3] This upper limit has been set for the same motivation of the cost constraint discussed above.

Table 18 Integrated Architecture Assessment Matrix for MSR

| Requirements | Alternative values | | | | No# of Options |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Drilling System Maximum Reachable Depth | Surface (~2.5cm) | 1-meter | 10-meter | | 3 |
| Total Number of Samples Collected | 10 | 20 | 30 | 40 | 4 |
| Sample Size | Small (0.5cm D x 1.0cm H) | Medium (1.0cm D x 5.0cm H) | Large (5.0cm D x 15cm H) | | 3 |
| Horizontal Diversity (characteristic radius) | 5 km | 10 km | 25 km | 50 km | 4 |
| Collect Sedimentary Material Samples | Yes | No | | | 2 |
| Collect Hydrothermally & Low Temp. Altered Samples | Yes | No | | | 2 |
| Collect Igneous Rock Samples | Yes | No | | | 2 |
| Collect Regolith, Dust & Atm. Gas Samples | Yes | No | | | 2 |
| | | | | Total No# of Possible Requirement Sets | 2304 |
| | | | | | |
| **Architectural Decisions** | **Architectural Options** | | | | **No# of Options** |
| | 1 | 2 | 3 | 4 | |
| Number of Elements | 1 ((Drill + Fetch + Return)) | 2 (Drill + (Fetch and Return)) | 2 ((Drill and Fetch) + Return) | 3 ((Drill) + (Fetch) + (Return)) | 4 |
| Mars Ascent Vehicle (MAV) Number of Stages | 1 | 2 | 3 | | 3 |
| Earth Return Vehicle (ERV) Number of Stages | 1 | 2 | | | 2 |
| Mars Ascent Vehicle (MAV) Propulsion Type | Solid | Storable NTO/N2H4 | | | 2 |
| Earth Return Vehicle (ERV) Platform Type | MAV only | MAV + Orbiter | | | 2 |
| Earth Return Vehicle (ERV) Propulsion Type | Storable NTO/N2H4 | | | | 1 |
| | | | | Total No# of Architectures | 96 |
| | | | | | |
| | | | | Total No# of Integrated Architectures | 221184 |

### *4.4.2.6. Architecting Model*

The architecting model has been implemented in MATLAB© and structured in modules as shown in the waterfall diagram in Table 19[4]. The model has been partitioned not to have feedback loops between modules. Feedback loops are usually found in system design models (a typical feedback loop in spacecraft design can be found between power and thermal subsystem models). Based on the experience of the author, such is rarely the case in architecting models featuring transportation architectures sized through first principles (i.e. rocket equation calculations). All units in the model are S.I. unless otherwise noted.

Table 19 Model Implementation Waterfall Diagram

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Model Inputs** | I2, I3, I4, I14, I31, I38 | I1, I5, I6, I7, I8, I9, I10, I11, I30, I34, I47, I48, I50 | I1, I12, I13, I15, I16, I17, I18, I19, I20, I41, I42, I43, I46, I48, I49 | I1, I12, I21, I22, I23, I24, I35, I41, I42 | I1, I25 | I1, I25, I26, I27, I28, I29, I32, I33, I36, I37, I39, I40, I44, I45, I1 | I16, I27, I28, I29, I30, | I3, I6, I11, I15 | |
| | **Samples Module** | O2, O3 | O1, O2, O5 | O3, O4 | | | | O2 | |
| | | **Caching (Driller) Module** | | | O7 | O7 | O12 | O6, O8, O9, O10, O11 | |
| | | | **Fetching (Sample Cache Retriever) and Mars Ascent Vehicle Module** | O15 | O15, O16 | O16 | O17, O22 | O13, O14, O18, O19, O20, O21 | |
| | | | | **Orbiter (Earth Return Vehicle) Module** | | O23 | O24 | O25, O26, O27, O28, O29 | |
| | | | | | **Entry Descent & Landing Module** | | | O34, O35 | |
| | | | | | | **Earth Departure and Mars arrival Vehicle Module** | O32 | O30, O31 | |
| | | | | | | | **Feasibility Check Module** | O33 | O33 |
| | | | | | | | | **Architecture Evaluation Module** | AE1, AE2, AE3, AE4, AE5, AE6, AE7, AE8, AE9, AE10 |
| | | | | | | | | | **Stakeholders Evaluation Module** |

[4] The nomenclature of the waterfall diagram can be found in Appendix 9.2

The following modules have been implemented:

- **Model Inputs:** This module includes parameters that have been assumed throughout the analysis. Table 20 provides a synopsis of the parameters used in the architecting model.

Table 20 Parameters used in architecting model

| Parameter Name | Parameter Value | Parameter Description |
|---|---|---|
| MI_SampleContainerDimOverhead | 1/17 | Sample Container Size Overhead Parameter |
| MI_SampleContainTareFraction | 0.04 | Sample Container Tare Fraction |
| MI_MAVDiameter | 0.40 | MAV Diameter |
| MI_MAVInterstageHeightFraction | 0.61 | MAV Interstage Height Fraction (w.r.t. Total Tanks Height) |
| MI_ERVInterstageHeightFraction | 0.61 | ERV Interstage Height Fraction (w.r.t. Total Tanks Height) |
| MI_EDLMassFraction | 0.30 | EDL Payload Mass Fraction |
| MI_EDVDiameter | 4.50 m | EDV Diameter |
| MI_EDVPropulsionType | 1 | EDV Propulsion Type (NTO/N2H4) |
| MI_SampleDensityMatrix(1) | 3000 kg/m3 | Sedimentary Materials Density |
| MI_SampleDensityMatrix(2) | 2500 kg/m3 | Hydrothermally & Low T. Altered Rocks Density |
| MI_SampleDensityMatrix(3) | 2750 kg/m3 | Igneous Rocks Density |
| MI_SampleDensityMatrix(4) | 1100 kg/m3 | Regolith and Dust Density |
| MI_dV_LEO_LMO | 4500 m/s | Delta V from Low Earth Orbit (LEO) to Low Mars Orbit (LMO) |
| MI_dV_LMO_MS | 1400 m/s | Delta V from LMO to Martian Surface (MS) |
| MI_dV_MS_LMO | 4100 m/s | Delta V from MS to LMO |
| MI_dV_LMO_LEO | 2600 m/s | Delta V from LMO to LEO |
| MI_dV_LEO_GND | 0 m/s | Delta V from LEO to Earth Surface (GND) |
| MI_EDVPropellantDensity | 130 kg/m3 | EDV Propellant Density |

| | | |
|---|---|---|
| MI_EarthGravity | 9.81 m/s2 | Earth Gravity |
| MI_OrbiterContingency | 0.43 | Orbiter Mass Contingency |
| MI_RoverSystemContingency | 0.43 | Rover Systems Mass Contingency |
| MI_RoverInstrumentPackMass | 30.6 kg | Rover Instrument Package Total Mass |
| MI_FetchPayloadMassFraction | 0.09 | Fetch Rover Payload Mass Fraction |
| MI_CachingPayloadMassFraction | 0.18 | Caching Rover Payload Mass Fraction |
| MI_LOXDensity | 1141 kg/m3 | LOX Density |
| MI_LH2Density | 130 kg/m3 | LH2 Density |
| MI_AeroShellDiameter | 1200 kg/m3 | Aeroshell Diameter |
| MI_ERVDiameter | 4.5 m | ERV Diameter |
| MI_FetchRoverSystemContingency | 0.30 | Fetch Rover System Contingency |

- **Samples Module:** The samples module assumes a sample container payload mass fraction to size the sample container as a function of the total mass of collected samples.
- **Caching (Driller) Module:** The caching module provides a preliminary sizing of the rover system based on payload mass fraction principles. Payload mass fractions have been estimated from the MSR baseline. Payload mass is estimated as the sum of in-situ science instruments mass (defined as parameter in the model) and drilling payload mass. Drilling payload mass is estimated using a parametric model that has been developed based on actual and proposed drilling payloads (see Appendix 9.2 for details on this model). Drilling payload mass is estimated as a function of drilling depth.
- **Fetch and Mars Ascent Vehicle Module:** The fetch rover is estimated using payload mass fractions. Fetch payload is incorporated in drilling and caching payload in corresponding 2 element architectures where drilling and fetching functions are incorporated, allow mass savings in that a dedicated fetch rover is not required. It further estimates the dry and wet mass of the Mars Ascent Vehicle. The delta V capability of the MAV depends on the concept of operations selected in the architecture, i.e. whether the MAV is supposed to deliver the Sample Container in Low Mars Orbit or to deliver the Sample Container directly to Earth surface.
- **Earth Return Vehicle Module:** This module estimates the dry and wet mass of an Earth Return Vehicle (i.e. an orbiter) based on payload mass fractions and first principles (i.e. rocket equation

calculations). Those masses are zero in architectures where the MAV retrieves samples directly to Earth surface.

- **Entry Descent and Landing Module:** this module estimates the mass of the Entry Descent and Landing (EDL) system required to land an entry mass estimated by the other modules of the model. The module incorporates the model that has been developed and is presented in Section Three that estimates EDL mass as a function of entry velocity, entry mass and an average ballistic coefficient estimated through comparison with analog Mars missions.
- **Earth Departure and Mars Arrival Vehicle Module:** this module estimates the mass of an Earth Departure vehicle. This feature being deactivated in the latest version of the model where it is always assumed that the launch vehicle will provide the delta V for Trans Mars Injection. It is maintained as legacy module in case future studies will desire to consider Earth Departure Stage tradeoffs in design space exploration.
- **Feasibility Check Module:** this module prunes unfeasible architectures from the design space based on pre-defined user constraints. Constraints implemented in the current version of the model are on allowable payload volume to fit within existing launch capability and logical constraints such as prune architectures featuring unfeasible transportation options.
- **Architecture Evaluation Module:** this module evaluates architectures according to pre-defined metrics that include objective metrics such as dry mass and cost and subjective metrics.
- **Stakeholder Evaluation Module:** this module evaluates architectures according to subjective metrics estimated through value judgment elicitation from experts such as scientific and engineering multi-attribute utility functions.

#### *4.4.2.7. Model Validation*

The model has been validated by simulating mass performance of a MSR architecture resembling the baseline presented in the National Academy Reports. Table 21 and Figure 37 show the data resulting from the validation of the model showing an adequate overall mass accuracy below 20%. Greater error in EDL mass results from discrepancies in the assumptions in the entry velocity and ballistic coefficient of the current NASA baseline that were not available in the public literature. Should this data be available at some point for comparison, the model should provide better outcomes in validation of the EDL module. Section Three shows the validation of the model on past missions for which the ballistic coefficient and entry velocity were known, showing better accuracy in mass estimates.

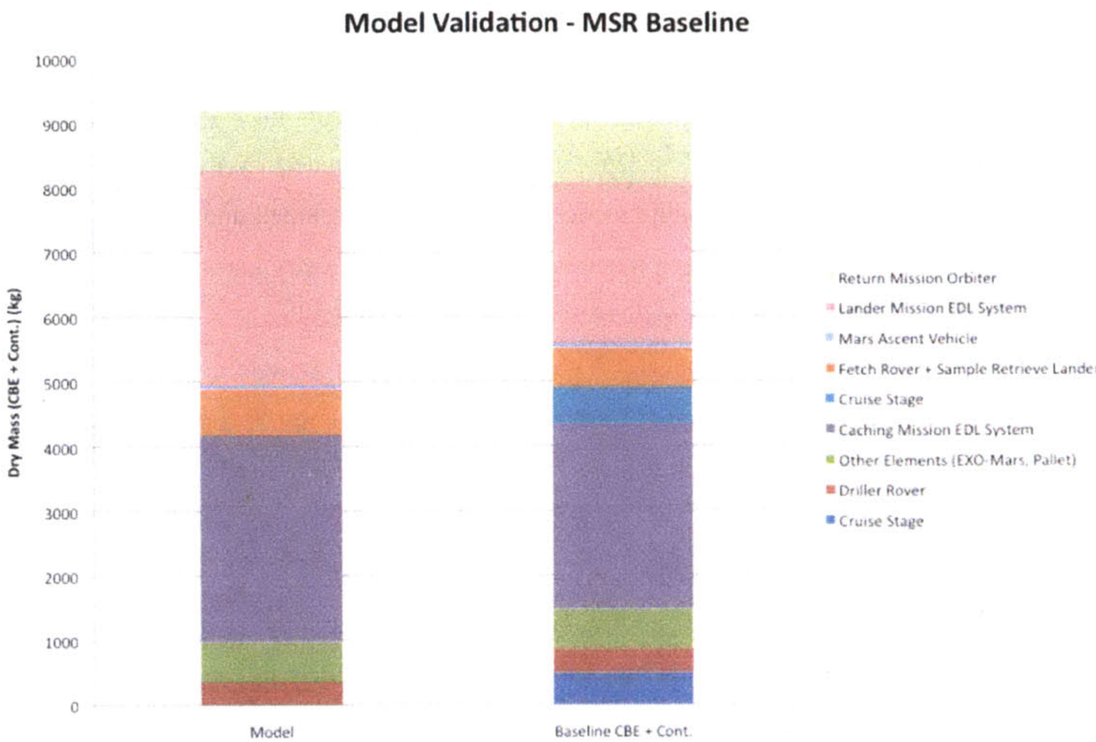



Figure 37 - Model Validation - Benchmark with MSR Architecture Baseline

Table 21 Model Validation - MSR Architecture Baseline Validation Data

| Baseline Validation | Dry Mass (kg) | | |
|---|---|---|---|
| | Model | Baseline CBE + Cont. | Diff % |
| Cruise Stage | 0 | 498.7 | N/A |
| Driller Rover | 354.3 | 364.5 | -2.8% |
| Other Elements (EXO-Mars, Pallet) | 627.5 | 627.5 | 0.0% |
| Caching Mission EDL System | 3202.3 | 2855.9 | 12.1% |
| Cruise Stage | 0 | 571.2 | N/A |
| Fetch Rover + Sample Retrieve Lander | 708.0 | 603.304 | 17.4% |
| Mars Ascent Vehicle | 64.1 | 72.2 | -11.2% |
| Lander Mission EDL System | 3321.9 | 2485.84 | 33.6% |
| Return Mission Orbiter | 926.8 | 942.9 | -1.7% |
| Total Dry Mass (CBE + Cont) | 9204.9 | 9022.0 | 2.0% |

*1. Development of Evaluation Metrics*

The metrics that have been developed for evaluation of architectures are presented in Table 22.

Table 22 Evaluation metrics for the Mars Sample Return Campaign case study

| Objective metrics | Units | Subjective metrics | Units |
|---|---|---|---|
| Total Dry Mass | kg | Utility to Scientists | - |
| Total Wet Mass | kg | Utility to Engineers | - |
| Total Lifecycle Cost | FY15 M$ | | |

*Multi-Performance Architecture Enumeration*

The model enumerates 221,184 possible architectures as overview previously in Section 4.4.2.6.

### 4.4.3. Step 3 – Expert Panel Formation

The expert elicitation questionnaire has been tested and calibrated with 5 "test pilot" interviews conducted with engineers and scientists at JPL and ESA. These interviews were not included in the assessment as they were used to refine the expert elicitation procedures. Two experts panels were composed for this study, representing science and engineering respectively. Experts were selected for the decision-making roles held in their organizations. Experts were recruited on a volunteer basis. Ideally, the goal was to obtain a balanced US-EU panel. However, as the study employed "real" senior experts and decision-makers and relied on voluntary contributions, a perfect 50/50 distribution could not be achieved. Obtaining expert availability outside of JPL (where the study was started) proved to be a challenge. More than 30 experts were contacted worldwide to obtain a total of 12 participating representatives. However, low participation was offset by proven experience and role of individual experts in their respective organizations. Furthermore, the study has been cross-validated *a posteriori* by comparison with current or previous Mars exploration architectures, and by presenting final results to larger poll of scientists and engineers. Lack of availability of ESA experts from the science side has been offset by recruitment of two scientists with Principal Investigator roles in European missions, affiliated to European universities. The number of scientists has been doubled with respect to the number of engineers as the observed variability on science measures was considerably higher than that observed for engineering assessments (as discussed in Section 4.4.8). An overview of expert panels composition is shown in Table 23.

Table 23 Expert Panel Composition

| Experts Affiliation | JPL | ESA | Academia (EU) | TOTAL |
|---|---|---|---|---|
| "Test pilot" interviews | 6 | 2 | - | 8 |
| Scientists | 6 | 0 | 2 | 8 |
| Engineers | 3 | 1 | 0 | 4 |
| | | | GRAND TOTAL | 20 |

### 4.4.4. Step 4 – Problem Formulation Review with Panel

An initial problem formulation has been outlined using information obtained by surveying the public literature on the Mars Sample Return campaign and on personal expertise of the author in space systems modeling. Successively, the formulation of the interview has been refined and extended through a "Round 0" interaction with "test pilots" from NASA JPL Mission Concepts Section and the JPL Mars Office.

### 4.4.5. Step 5 – Design of Interview

The interview has been designed using a multi-attribute utility. Two types of interview questionnaires have been elicited:

- An interview of **Scientists**, to estimate the scientific value of a given set of requirements for a MSR architecture;
- An interview of **Engineers**, to estimate the engineering difficulty perceived for the implementation of a given set of requirements (as a proxy of complexity and technical risk).

The interviews have been designed with the assumption that all interviewees are rational utility-maximizing individuals. That is, a utility value of 1 in the scientific interview translates to 100% satisfaction of the given science with a particular set of requirements. A utility value of 1 in the engineering interview means 100% satisfaction from an engineering perspective (100% ease in implementing the prescribed set of requirements). A utility value of 0 corresponds to no scientific value and very high-perceived difficulty in engineering implementation respectively.

Both the Scientific and Engineering interviews were based on MAUA formulations developed on the following attributes:

- Sample Types
- Total Number of Samples
- Sample Depth
- Sample Size
- Horizontal Traverse Distance

Sample Types have been modeled using a complementary discrete utility model. Total number of samples and horizontal traverse distance have been modeled as continuous utility functions using a combination of CEP/LEP interviews. Sample Depth and Sample Size have been modeled using mutually excluding discrete utility models.

### 4.4.6. Step 6 – Elicitation of Expert Value Judgment

Expert elicitation has been done through interviews conducted by the thesis author at NASA JPL, and by phone with experts in other institutions.

### 4.4.7. Step 7 – Results Analysis

Design space exploration results are analyzed at each step of the study to prepare the discussion in successive rounds with experts. If convergence is met (as discussed in Step 9), results analysis provides the data for documentation and development of recommendations (Step 10).

The study evaluates the design space of MSR architecture across 5 dimensions:

- Total Campaign Mass (Dry/Wet)
- Total Estimated Lifecycle Cost (FY15)
- Total Scientists Utility (as a proxy for science value)
- Total Engineers Utility (as a proxy for engineering difficulty)

Due to the multi-dimensionality of the problem, a set of multiple group scatter plots will be used in the discussion of the results. The analysis is structured to answer the questions formulated in Step 2 (Problem Formulation).

The remainder of this Section discusses results as derived from implementation of subjective value metrics for science value and engineering complexity as obtained at Round 3 of the analysis.

1. **Does the current MSR architecture provide an efficient compromise between desired science returns and engineering complexity? (i.e. how far is it from ideal Pareto efficiency?)**

**Finding 1: The current MSR architecture provides an efficient compromise between science and engineering at its level of cost** (Figure 38 - **$5.3B + ~0.5B for sample handling and containment as estimated by the model). Alternative architectures are conceived at different levels of cost and other levels of efficient science/engineering tradeoffs.**

Figure 38 shows the design space of MSR architectures in utility space. Architectures are color-coded based on their estimated total campaign lifecycle cost. The x-axis represents utility provided to scientists (i.e. science value), the y-axis represents utility provided to engineers (i.e. engineering complexity). The larger red dot on the upper-right corner of the plot shows the current MSR baseline architecture as evaluated by the model. The MSR baseline lies on the Pareto frontier as defined by utility functions elicited by experts. This provides confidence on the coherence of results of the design space exploration with existing value judgments. As some of the experts were directly involved in the definition of the baseline, they would be expected them to provide a positive evaluation of their own architecture. Once validated, the same value judgment criteria can be applied with increased confidence to the other options available in the tradespace.

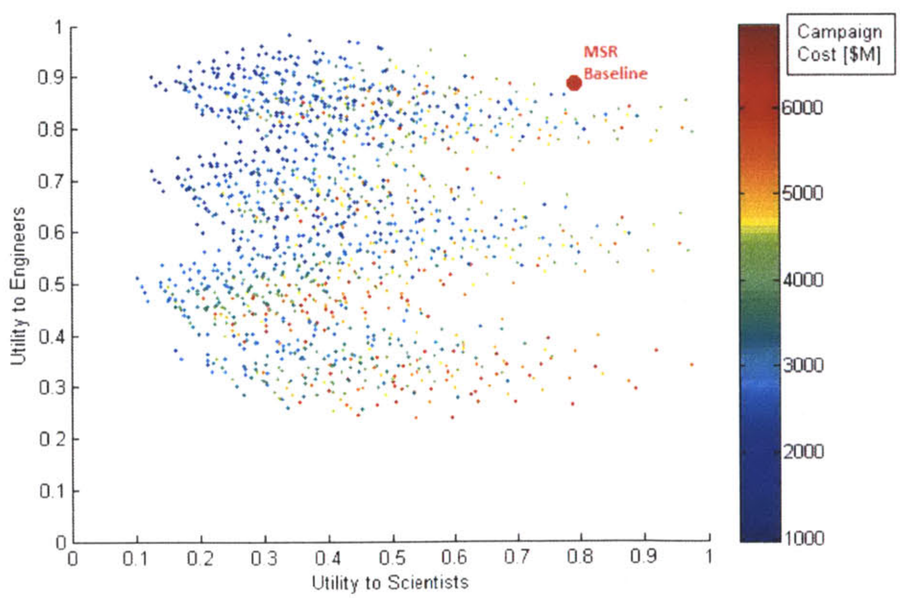



Figure 38 MSR Design Space, Science/Engineering/Cost (FY10) View

2. **What other Pareto-efficient MSR architectures could be devised for different levels of total cost?**

**Finding 2: Two element architectures are alternatives of interest for reduction of cost and schedule slippage (by reduction of total number of development projects). A two-element architecture of interest consists in transferring Fetch functionalities to the Drilling and Caching Rover, while extending the rover's operational lifetime and not requiring a dedicated fetch rover in the Return mission. If cost reduction is a concern, consider surface drilling operations only. Moderate reductions in total number of collected samples provides an alternative means of cost reduction, with its effectiveness being larger for architectures with 1-m and 10-m drilling payloads.**

Figure 39 and Figure 40 show that two or three element architectures at different values for total dry mass are available in the tradespace. One element architectures result infeasible with current launch capabilities not being able to carry all the mass required for a MSR architecture in one flight – the problem being both in payload mass and fairing volume capabilities. Two element architectures entail additional operational risk as they require the first Drilling and Caching rover to operate until landing of the Retrieve mission. Further analysis is encouraged to estimate the additional complexity in including Fetch payload in the first rover, and studying the break-even point in the tradeoff between extending the lifetime of said rover - therefore adding an additional marginal operational cost - versus development and operational costs of the Fetch rover concept. It is expected that the benefits of the first will outrank the latter.

The model provides additional information in terms of other efficient architectures that can be conceived at varying levels of cost. Comparison of Figure 38 with Figure 41 shows that *total cost* is largely driven by the total number of samples to be collected on the surface. On the other hand, comparison of results across further dimensions show that total cost gradient features a strong dependence on desired drilling depth. This is shown by assessing the impact of drilling depth on the overall campaign architecture. Three clusters of architectures can be identified in the design space – mapping to three different classes of feasible architectures. The analysis conducted in Figure 44 shows that those three architectural classes refer to the three different drilling depths examined in the study (surface – 1m – 10m), featuring three different gradients of total cost (increasing gradient per increasing drilling depth). The fourth drilling depth initially explored for study (100m) was taken out from the design space as it clearly emerged consensus from all experts in considering such depth extremely hard to achieve in a medium-long term time span and of science value not justifying such large technology investment.

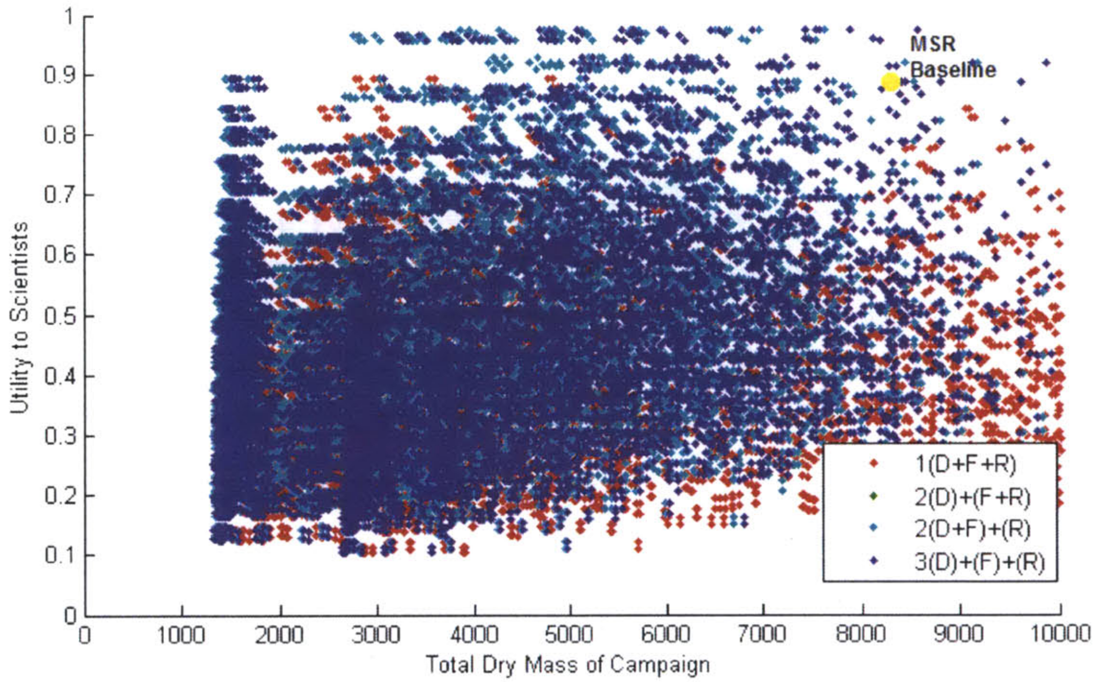



Figure 39 MSR Design Space, Mass/Science/Number of Elements View

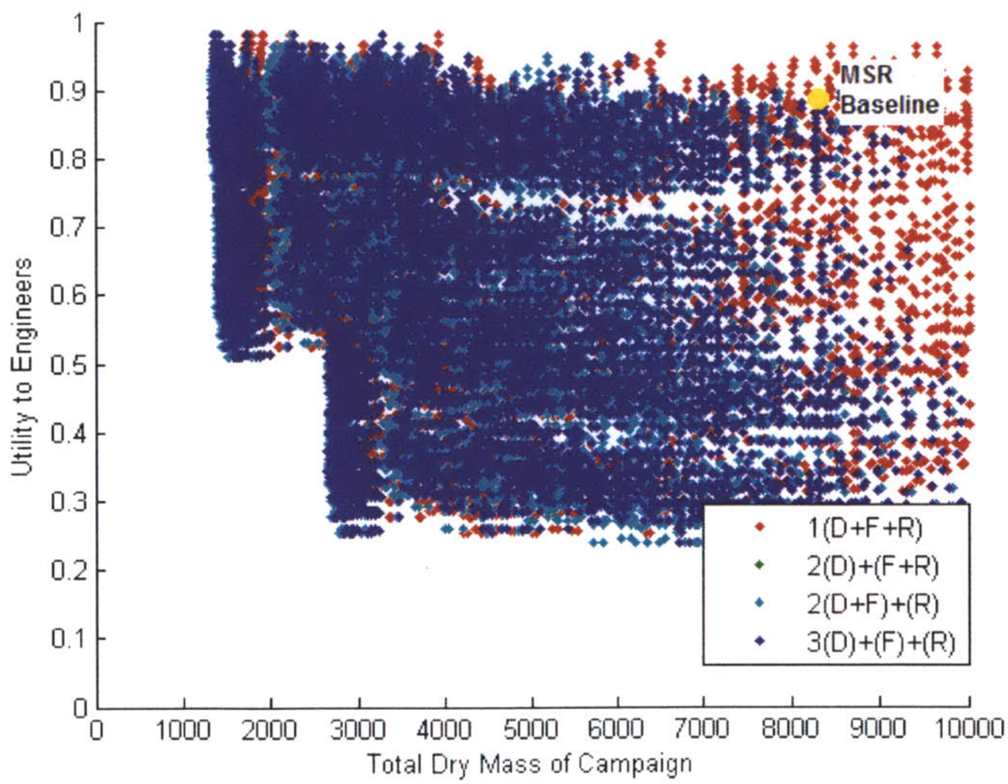



Figure 40 MSR Design Space, Mass/Engineering/Number of Elements View

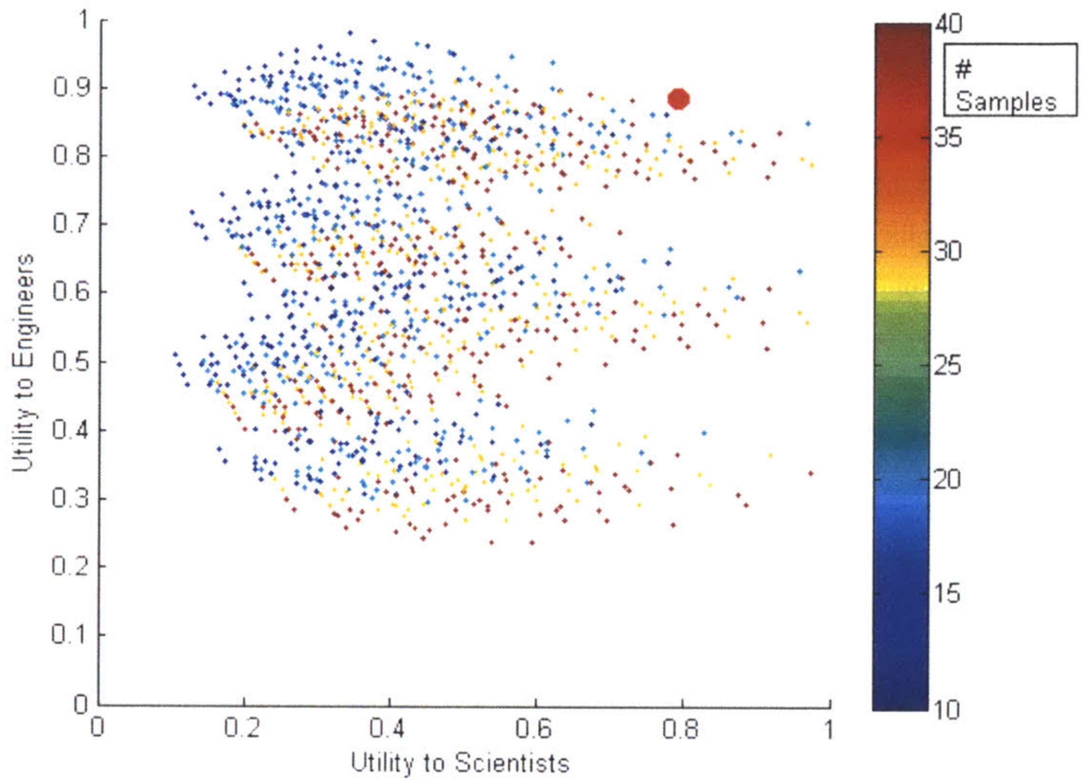



Figure 41 MSR Design Space, Science/Engineering/Total Number of Samples View

3. **What sample portfolio should MSR be designed for to maximize scientific returns?**

| **Finding 3: Sample portfolios with all types of samples dominate all other options.** |
|---|

Figure 42 shows that architectures with complete sample portfolios ('YYYY' architectures) lie in the Pareto front of the design space. This result is due to the fact the sample type providing the majority of scientific value (Sedimentary Materials) also results being the sample type with the highest density across all sample types (3000 kg/m3). Therefore, for the same mass of retrieved samples, architectures including sedimentary materials always result of higher scientific interest than sample portfolios without sedimentary material.

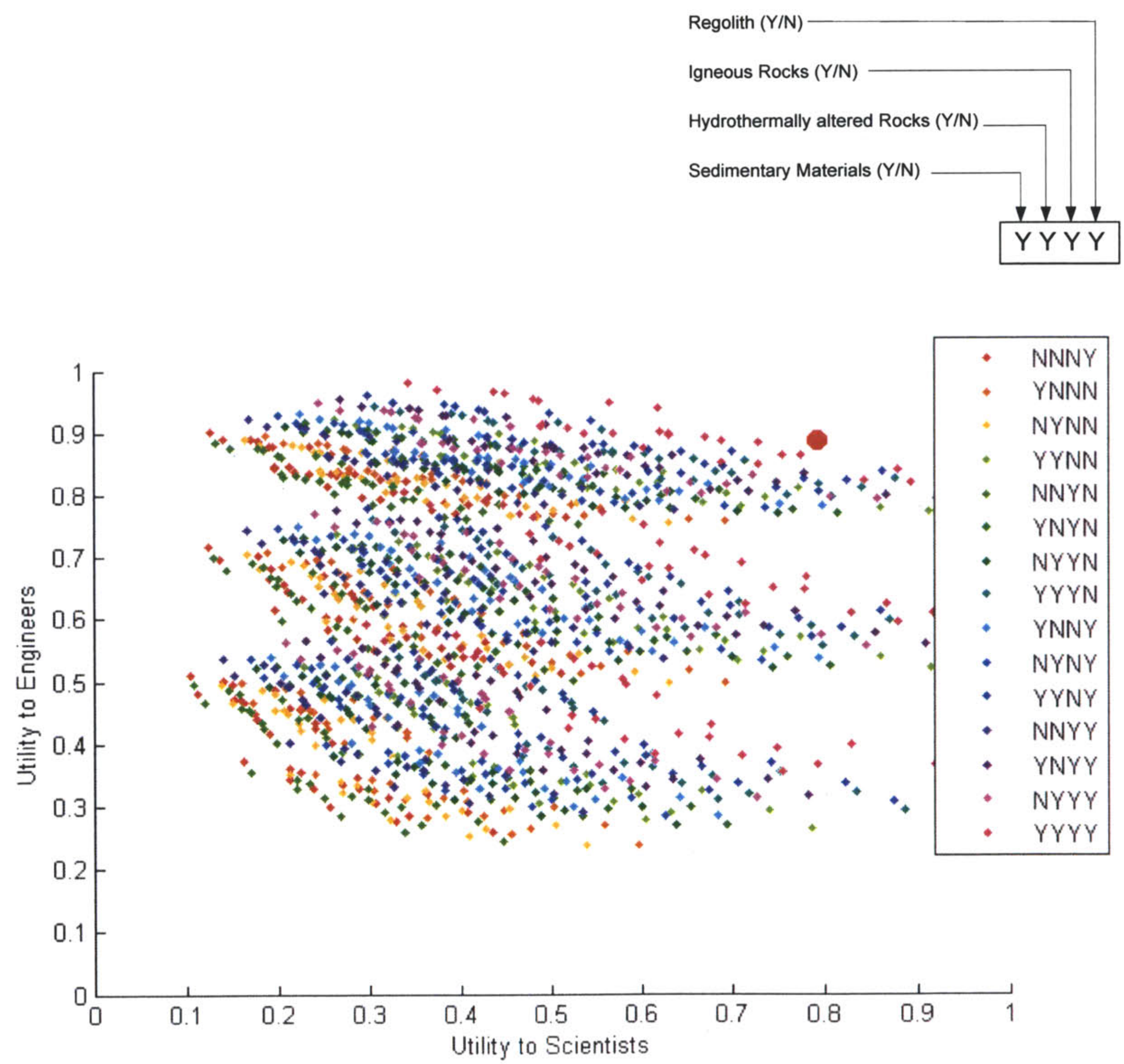



Figure 42 MSR Design Space, Science/Engineering/Sample Types View

4. **What sample size should MSR be designed for optimal tradeoff between scientific returns and engineering complexity?**

| |
|---|
| **Finding 4: Small and medium samples are feasible options in the design space. Medium-sized samples (such as the ones in the current MSR baseline) provide a systematic advantage in science utility with respect to small samples for a small increase in engineering complexity.** |

Figure 43 shows that medium-sized samples are closer to the Pareto frontier than small-sized samples. The ratio between the variation of science value and the variation in engineering complexity for an increasing number of samples of the same sample size is greater than one across all architectures. This shows that therefore medium samples are always preferred to small samples. Large-sized samples are ruled out from the feasible region of the design space resulting in architectures either exceeding $10B in total campaign cost and/or 20mt in total campaign dry mass.

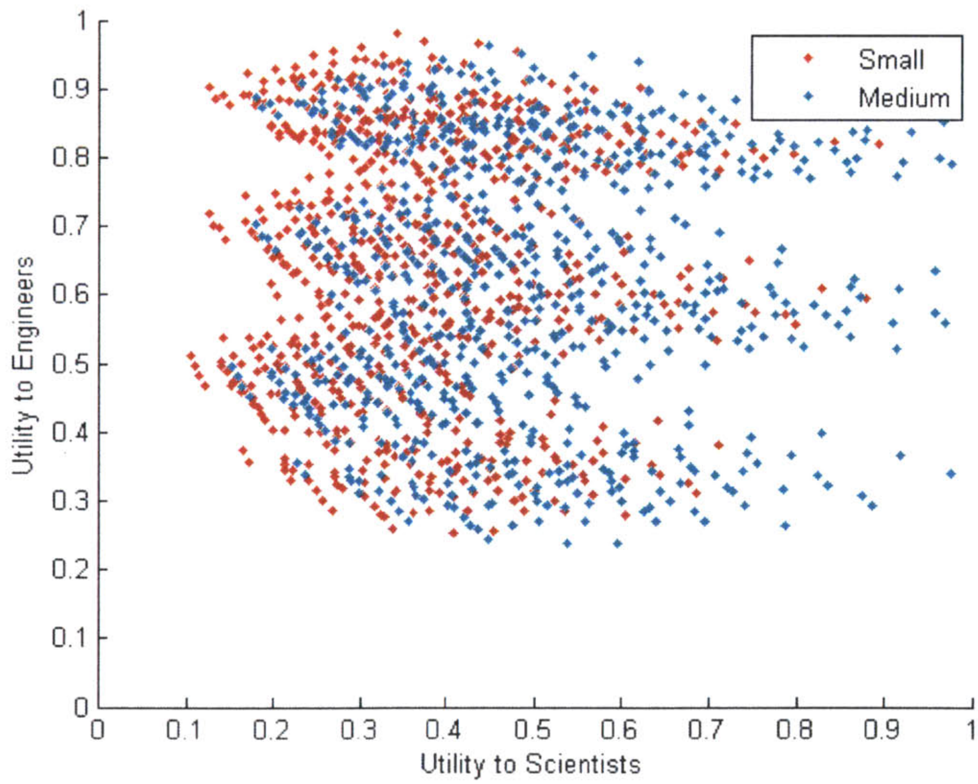



Figure 43 MSR Design Space, Science/Engineering/Sample Size View

**5. Is it worthwhile for MSR to accept the risk and invest in technology to retrieve samples beyond surface drilling (i.e. > 2.5cm)?**

**Finding 5: Surface drilling alone provides up to ~80% of the scientific value while retaining >~90% of the engineering utility across all the architectures in the feasible region of the design space.**

This result is based on the assessment by experts in Round 1 of this study. This result will be refined in successive interview rounds, although it is not expected to vary significantly. While deeper drilling depths enable fulfilling a greater number of scientific questions (in particular in the field of astrobiology), they involve a significant decrease in engineering utility reflecting the added technical complexity, technical and operational risk involved in developing "deep drilling" of the Martian surface. Challenges in planetary drilling include constraints in mass due to launch capability and allowable fairing volume, constraining the available Weight on Bit[5] (WOB) and posing issues in thermal control, drill bit cooling, bit preservation and fluid circulation to enable deeper drills.

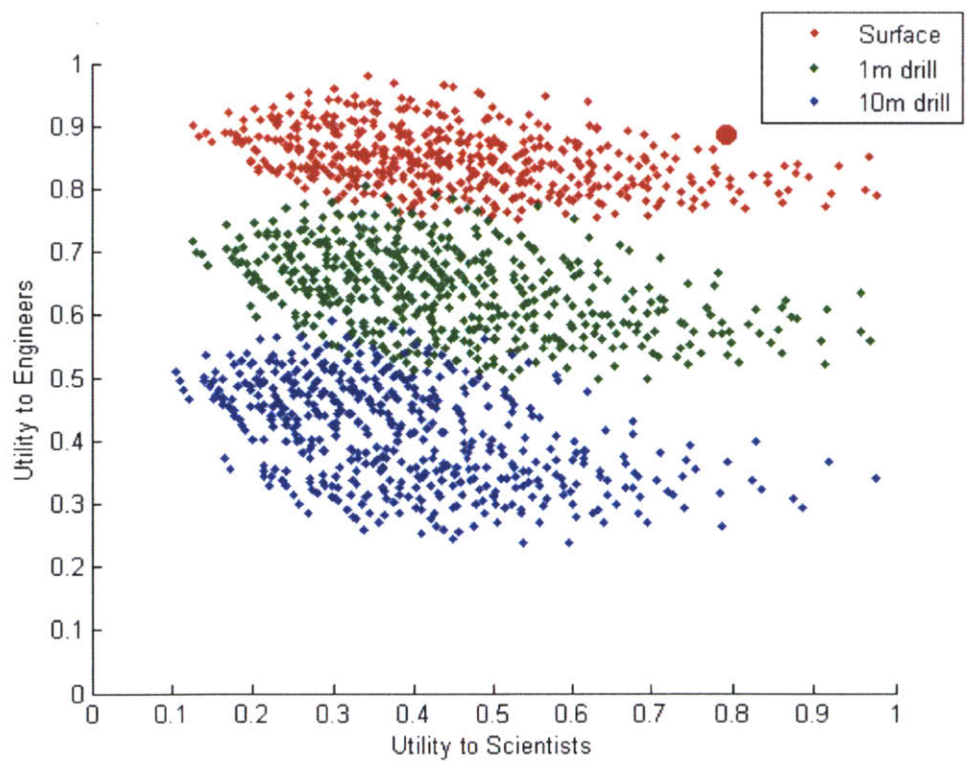



Figure 44 MSR Design Space, Science/Engineering/Drilling Depth View

[5] Weight on Bit is the force that can be exerted on a drilling bit, which is directly related to the performance of a given drilling payload. Further detail is available on the description of the drilling payload sizing model discussed in Section 9.2.4.4 (Appendix).

6. **Is it worthwhile for MSR to accept the risk of extending horizontal mobility for distributed sample caching and in-situ science investigations?**

**Finding 6: Extended horizontal mobility increases expected science value as it adds flexibility in sample selection and landing site selection. The associated cost in decreased engineering utility is small if comparing architectures with mobility systems.**

Figure 45 shows the impact of the requirement in horizontal mobility in the design space of feasible architectures. Horizontal mobility provides the operational flexibility to the caching and sampling system of choosing samples for successive collection. As scientists are concerned with the ability of selecting samples to increase the likelihood of relevancy to answer questions of interest, it is critical for sampling systems to attain mobility. For this reason, lander systems (i.e. caching systems with no horizontal mobility) have been ruled out in the formulation of the study. Once mobility is implemented, design space analysis shows that additional range in mobility is attained for a small marginal decrease in engineering utility, while providing a moderate-to-high marginal increase in perceived scientific value. Further study is recommended to study the marginal operational cost in extending the lifetime of the caching/sampling rover to allow an increased horizontal mobility, or alternatively study the marginal increase in operational risk of increasing the rover's driving speed for a fixed lifetime.

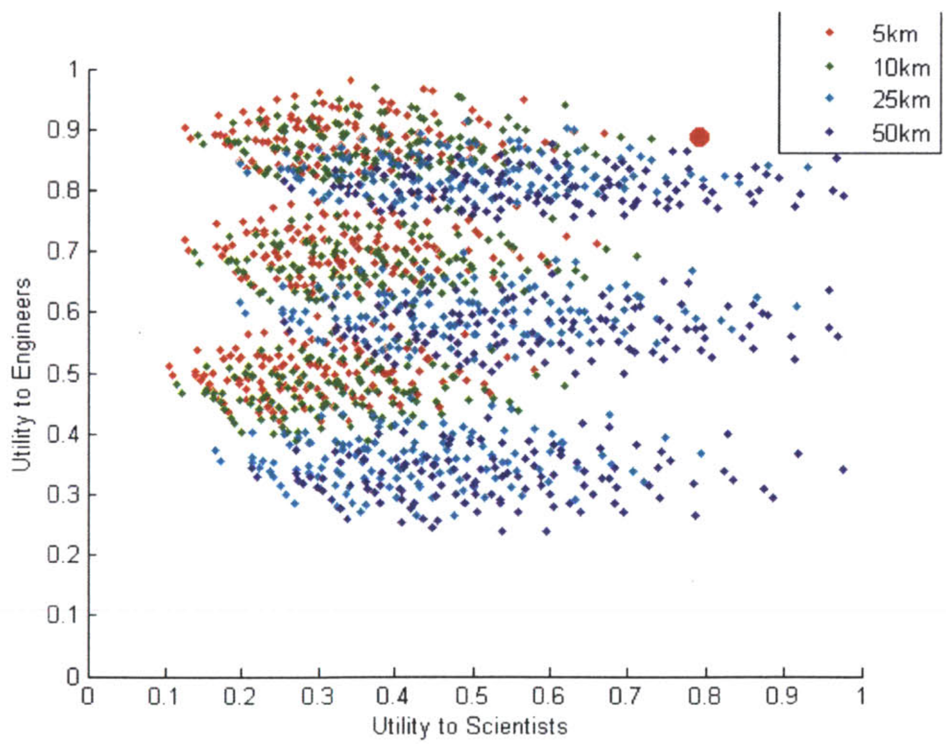



Figure 45 MSR Design Space, Science/Engineering/Horizontal Mobility View

### 4.4.8. Step 8 – Aggregate Results Discussion

Section 4.4.7 has discussed Round 3 results. This section provides additional discussion of the evolution of results during iterative rounds of analysis and discusses the impact of requirements ambiguity on the architectural tradespace.

Boxplot charts have been used to aggregate results and facilitate negotiations with individual experts during DB-SAF elicitation. Experts have been asked to revise their answers in light of the aggregate of the answers provided by other experts in the group. Figure 46 (Round 1), Figure 47 (Round 2), and Figure 48 (Round 3) show the evolution of answers in the three Rounds for the engineering panel, whereas science panel evolution is shown in Figure 49 (Round 1), Figure 50 (Round 2), and Figure 51 (Round 3).

The first empirical observation to make is the significant difference in convergence between engineering and science panels. Engineers were able to achieve agreement more rapidly and in more areas between Round 1 and Round 2. A significantly larger relative divergence was observed in the science panel. As an initial mitigation to this phenomenon, the science panel was doubled in size, by interviewing additional experts. These experts were given Round 1 interviews, and their answers were included in Round 2 computations. This addition of experts did not increase or decrease observed variability significantly, therefore confirming preliminary findings.

Larger variability on science value with respect to engineering complexity metrics is reasonable to expect. While engineers have a firm sense on what are current and foreseen technological constraints, science is more concerned with the exploration of the unknown. Scientists do not know value associated to a mission until a mission is actually flown, and experimental hypothesis verified on the field. While science value is linked to breakthrough discoveries and the exploration of the unknown, engineering follows a more predictable process, meaning that if the system is designed with appropriate margins of safety, and integrated, verified and validated against properly stated requirements, little is left to the unknown.

For instance, engineers were very efficient in reducing ambiguities on contributions given by sample types and sample depth in their complexity assessment (compare engineering round 1 results in Figure 46 with round 3 results in Figure 48). Design complexities associated with sample types were associated with technological challenges associated with coring and sampling operations with sample materials of different mechanical properties. Likewise, sample depth was associated with complexities in drilling operations, such as the need for 1-meter drilling and below to split the drilling rod in multiple segments and require a drilling rod assembly mechanism, compared to surface and sub-surface drilling that can be performed with rock abrasion tools. Ambiguities on those property variables were immediately recognized and reduced by the engineering expert panel in Round 2 interviews, through anonymous exchange of opinions by means of the interviewer. Ambiguities in the definition of engineering complexities were all reduced, as engineers came to consensus. Such was not the case for the science panel.

Scientists were driven by different and sometimes contrasting goals. The first challenge was reaching an agreement in ground assumptions and definitions. While this could be done in several instances - for instance, in assuming that only 30% of collected samples are supposed to be scientifically relevant after analysis on Earth – disagreement remained in several areas. In particular, no agreement was reached on science value associated with igneous rock samples – which are of interest only to scientists with interest in planetary interiors and planetary dating, for instance. Likewise, no agreement was reached on the value associated with target drilling depths beyond 1 meter. While astrobiologists associated very high value to these depths, geologists preferred obtaining shallower samples for their purposes. Both these areas were categorized as irreducible ambiguities, in terms of open debates. This conclusion helped inform the results discussed in the previous section. The dichotomy in "needs" and "wants" of astrobiologists and geologists has been clearly identified by the study.

It must be highlighted that both panels were composed by senior experts and high-level decision makers, with multiple years of experience in contributing to the systems architecting process of exploration missions to Mars. This is, however, a double-edged sword: while the expert sample is fully representative of the Mars Sample Return decision-making community from American and European perspectives, a potential bias is introduced in having the majority of panelists being senior experts in their respective fields. Biases are introduced by their professional experience in the field, having analyzed systems trade-offs for MSR in multiple occasions. This bias is confirmed in the analysis – but it would be strange otherwise – by the fact that the MSR baseline was included in the Pareto frontier in the results discussed in Step 7. This aspect has been partially mitigated by having an international composition of the panel with both American and European perspectives – as US and EU space agencies are the historical major developers of robotic exploration missions. Nevertheless, this is an aspect to account for as an inherent feature of the proposed framework. Results of the model are no better than the inputs that were provided. Nevertheless, the model that has been developed is able to evaluate quickly a very large amount of system architectures, by using the same logic employed by the panel of experts. This feature allows decision-makers to screen a much higher number of requirement sets and architectures that could be done by conventional pre-phase A study. This represents one of the main value-enhancing contributions of the application of the comprehensive systems architecting approach to Mars Sample Return design.

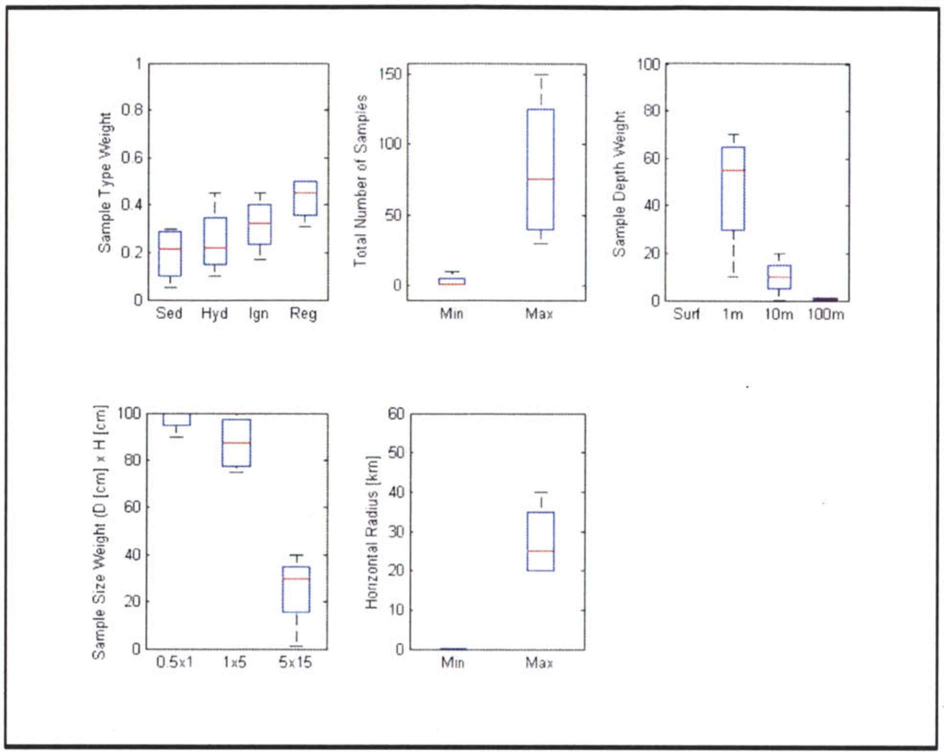



Figure 46 Engineering Panel - Round 1

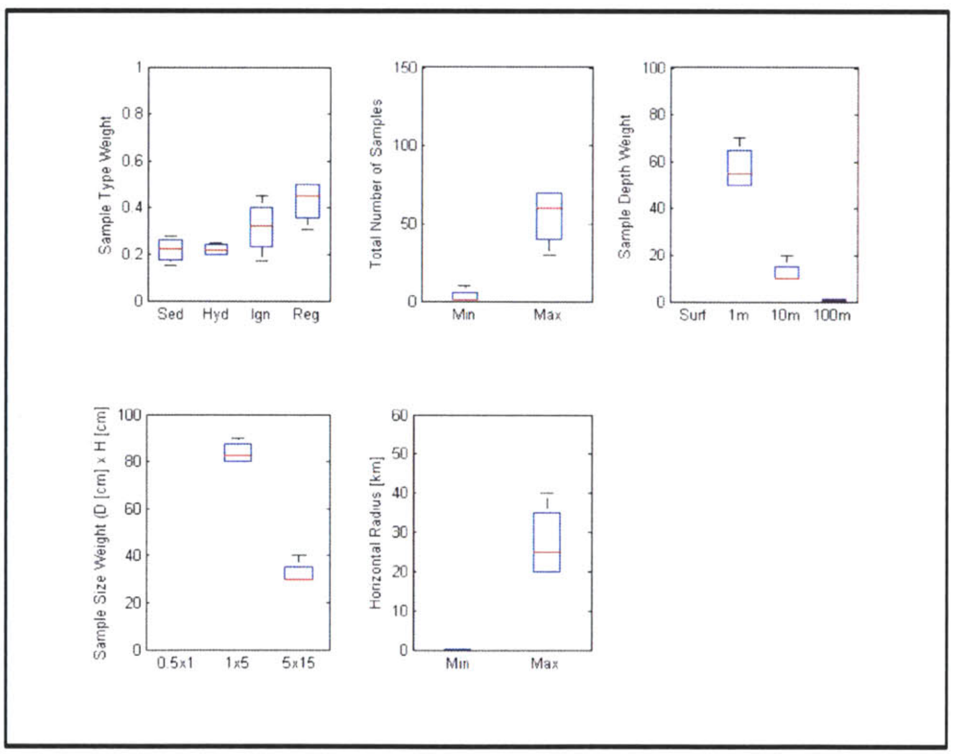



Figure 47 Engineering Panel - Round 2

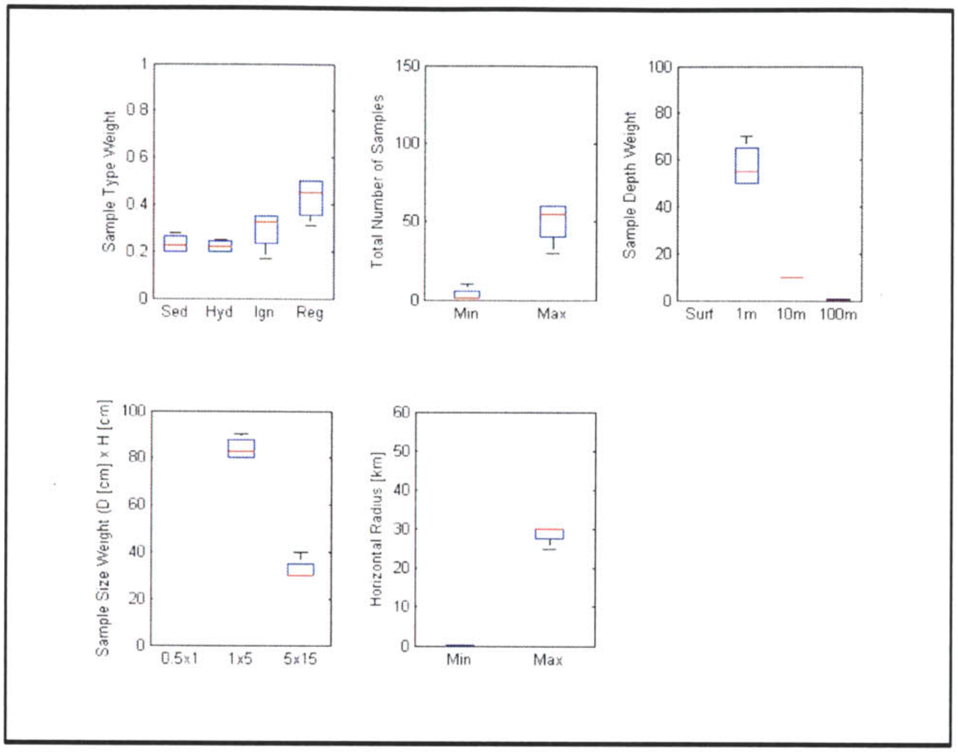



Figure 48 Engineering Panel - Round 3

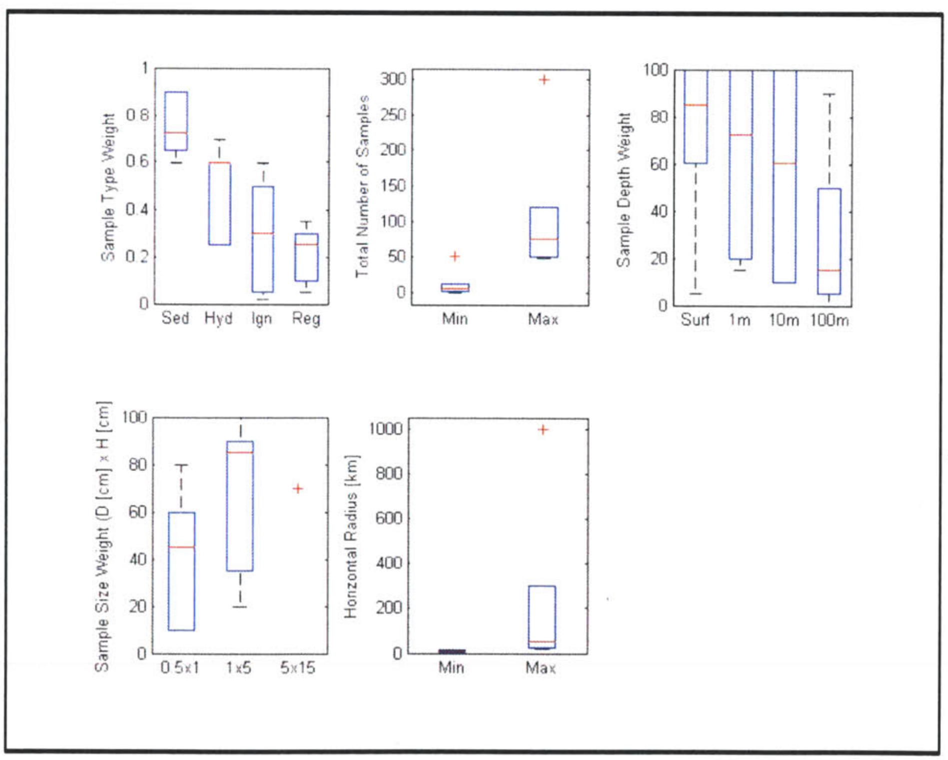



Figure 49 Science Panel - Round 1

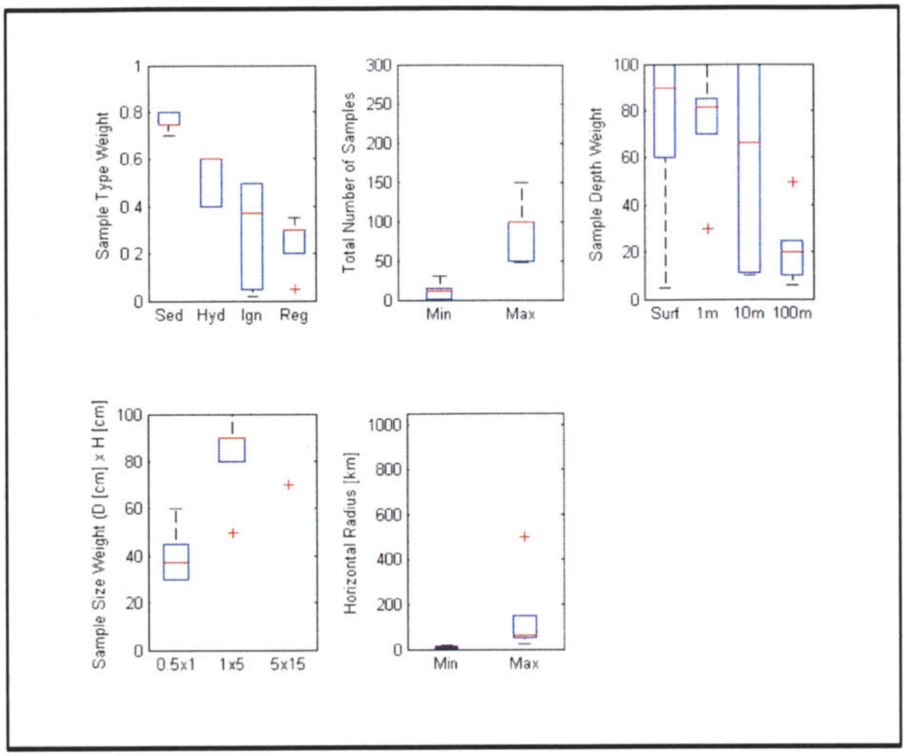



Figure 50 Science Panel - Round 2

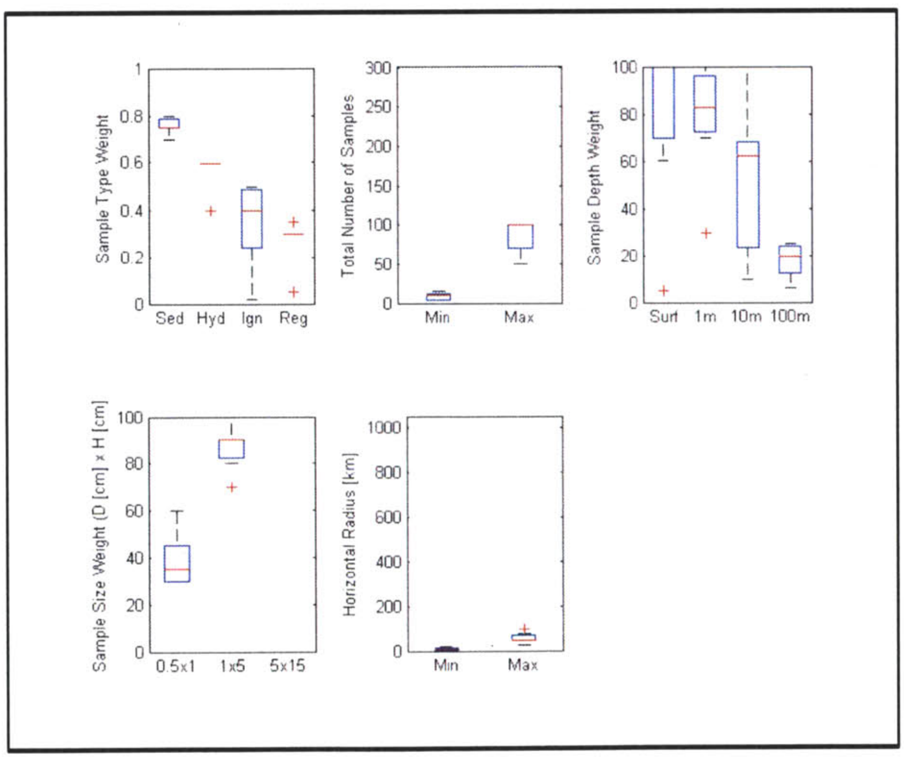



Figure 51 Science Panel - Round 3

We now assess the impact of irreducible ambiguities that have been identified on performance evaluation within the architectural tradepsace using Ambiguity Impact Analysis as discussed in Section 3.6.9.

Figure 52 shows the results of a main effects analysis on ambiguity impact. The x-axes on the plots show requirement variables and possible values they can assume in accordance to the requirements morphological matrix discussed previously in Section 4.4.2.4. The y-axis on the plots is the average effect of requirement variables on campaign cost normalized to the maximum and minimum cost values observed in the architectural tradespace – absolute cost numbers are not relevant in this context as we are interested in relative rather than absolute effects. Campaign cost is a proxy variable for architecture performance, as the model employs mass-based cost models. The analysis shows that requirement variables have varying impact on the architectural tradespace. From highest to lowest impact, their rank is the following:

1. Sample Size
2. Drilling Depth
3. Total Number of Samples
4. Total Number of Missions
5. Sample Types
6. Horizontal Mobility

This result shows that main impacts are largely related to requirements driving the sizing of payload masses on the Martian surface. By comparing impact analysis results with the DB-SAF results shown in Figure 48 and Figure 51, drilling depth emerges as the area in requirements analysis where system architects will need to concentrate on. Drilling depth has significant impact on campaign cost (rank #2), while being the area with most irreducible ambiguity, with particular reference to science value associated with drills of increasing depth. On the other hand, it is shown that ambiguity on sample types to be collected on the Martian surface has little effect on the architecture, given the assumptions that have been used in this model. Particular care should be exercised in the interpretation of this result, as this requires confirmation by a detailed design iteration of caching and handling mechanisms required with different sample types, which could represent significant drivers to total cost.

Another result of interest, confirming findings that have been previously described, is the main effect on total cost of the number of missions in the architecture, representing different packaging of functions within a varying number of elements. The 2-element architecture where Drilling and Fetch functions are combined minimize total cost (hence minimize total mass) due to the elimination of the Fetch rover platform from architecture. It must be noted though that operation risk increases in this type of mission, as more responsibility is given to the Caching/Drilling rover – which reliability therefore is on the critical path for successful completion of the mission.

Consider now the interaction between requirement variables to investigate the occurrence of interactions between requirement variables and their impact in the architectural tradespace. Sample types are taken out from this analysis for simplicity, as their interaction analysis confirmed the finding of their little relevance in affecting the overall tradespace. Figure 53 shows the results of this analysis; this matrix plot shows interactions between variable pairs. Features of interest include crossings – indicating inversions in the effect structure - and magnitude of effects. Such magnitude is comparable to what has been found in the main effects analysis, and no major interactions are highlighted. This analysis therefore confirms results found with the main effects analysis of ambiguity impact on the tradespace.

We now apply correlation analysis to study the impact of ambiguities in the tradespace from a different perspective. Figure 54 shows a scatter plot diagram with results for correlation analysis as conducted on the Mars Sample Return case study. Each plot results from the intersection of 5 metrics, namely campaign cost, utility to engineers, utility to scientists, standard deviation associated to utility to engineers, and standard deviation associated to utility to scientists. For instance, the subplot on the second row, third column, compares utility to scientists with utility to engineers – the same plot analyzed before in Figure 38. Plots on the diagonal show the distributions of each metric in the tradespace. Note that the plot is symmetric with respect to the diagonal.

Results of interest for the analysis of ambiguities can be found on the $4^{th}$ and $5^{th}$ rows and columns, associated to standard deviations in engineering and science panels respectively. Conclusions can be derived by assessing the impact of the variable of interest on the tradespace. Consider for instance the assessment of ambiguity associated with maximum drilling depth in engineering (Figure 55) and scientific value (Figure 56) assessments. By comparing these charts, it is clear that such ambiguity has a significant effect in engineering complexity with increasing drilling depth. This is confirmed by conversations with engineers involved in the design of drilling payloads in exploration missions, as discussed previously in this chapter. Associated benefits of deep drills, as shown in Figure 56, are modest if compared to associated complexities. Decision-makers can use correlation analysis, for instance, to defer the implementation of new drilling systems, waiting for ambiguity to unfold. Similar analysis can be conducted for other architectural variables of interest.

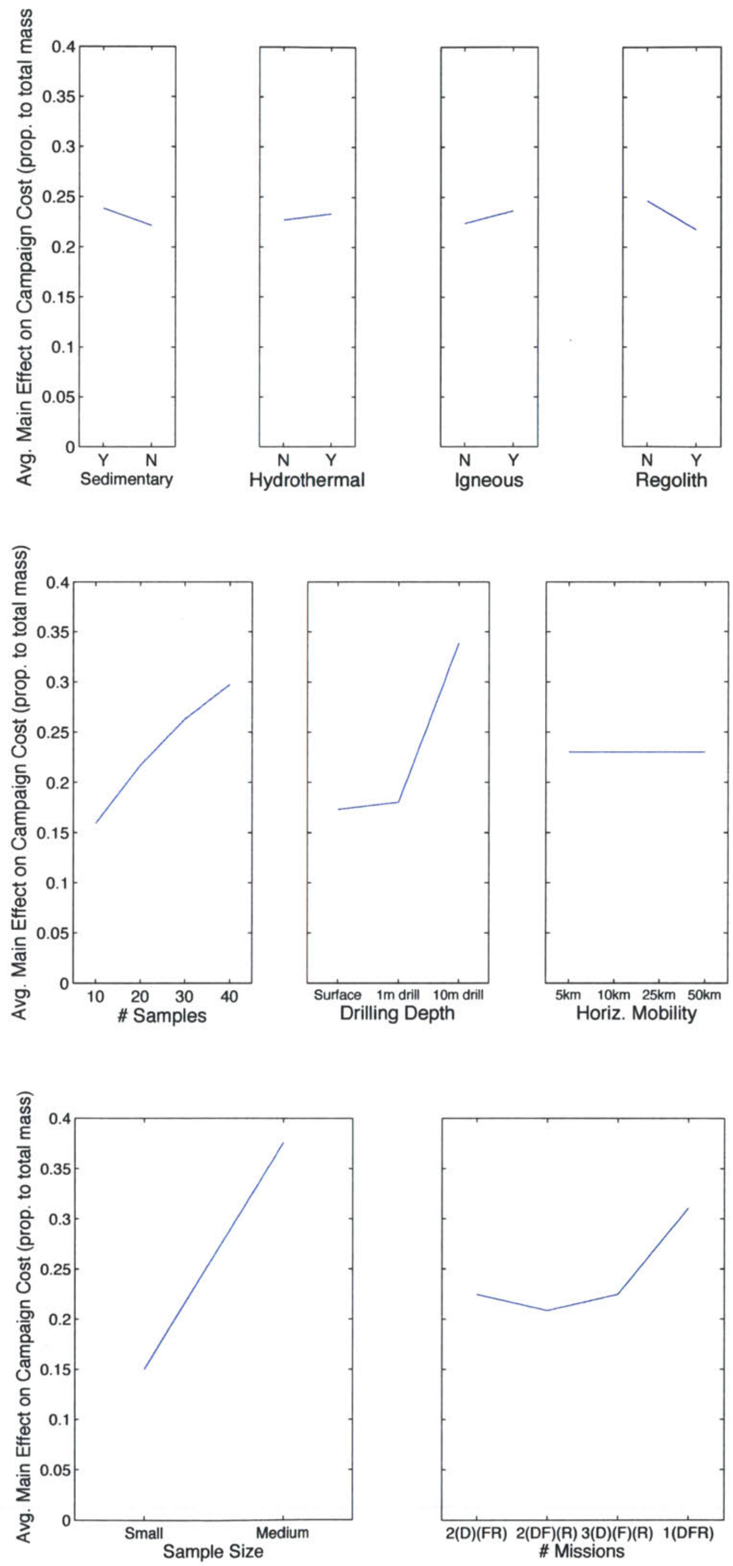



Figure 52 Mars Sample Return Ambiguity Impact Analysis - Main Effects

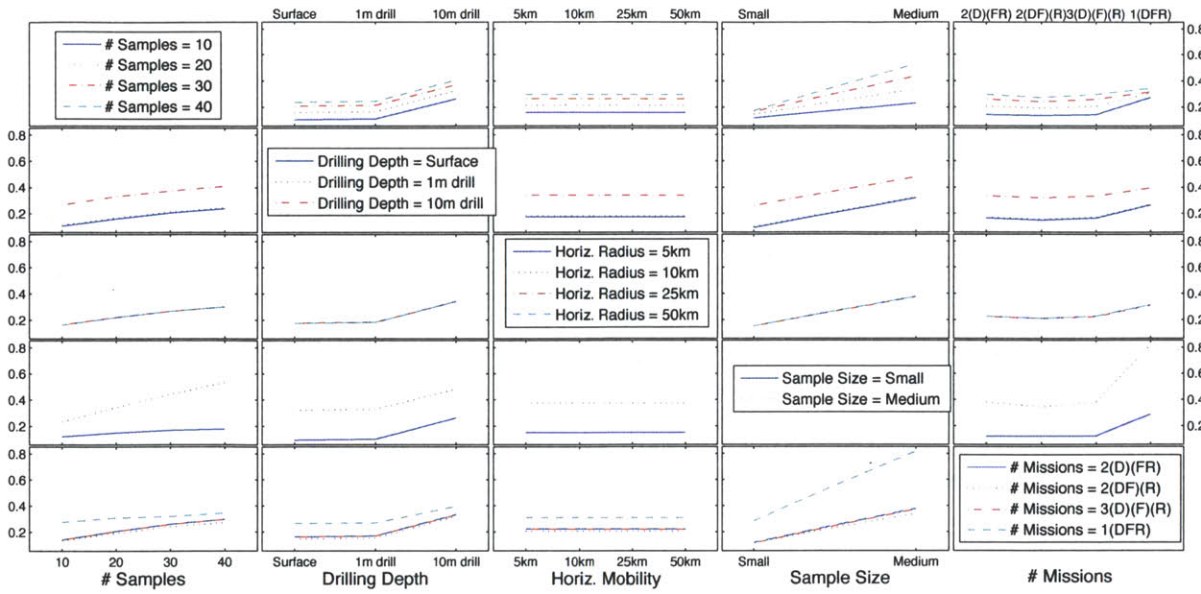



Figure 53 Mars Sample Return Ambiguity Impact Analysis - Main Interactions

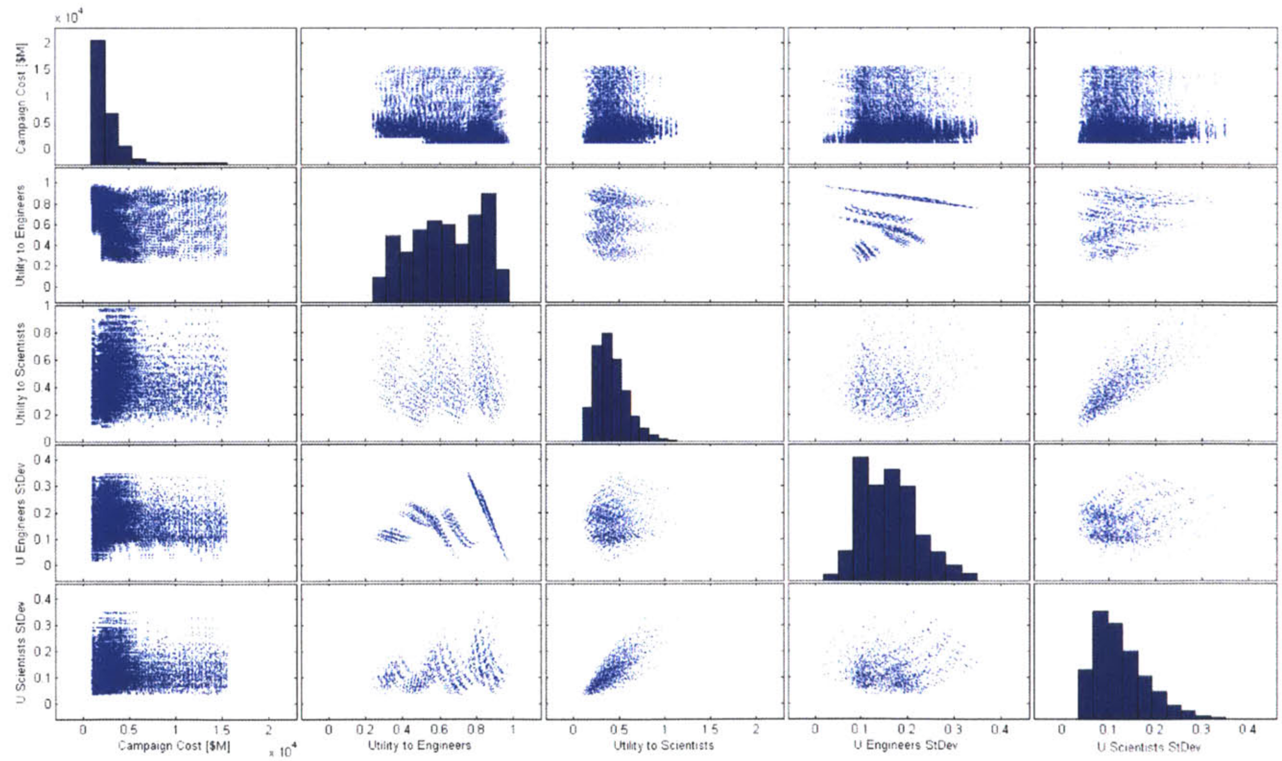



Figure 54 Correlation Analysis Results

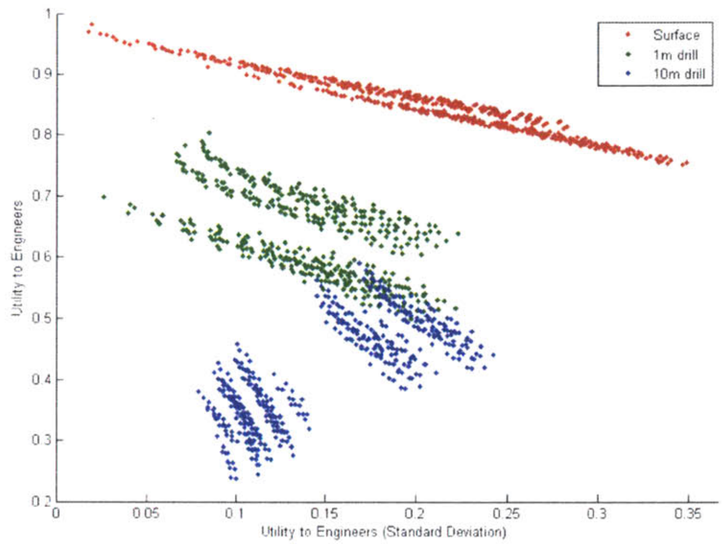



Figure 55 Impact of Drilling Depth Ambiguity on Engineering Complexity Value Assessment

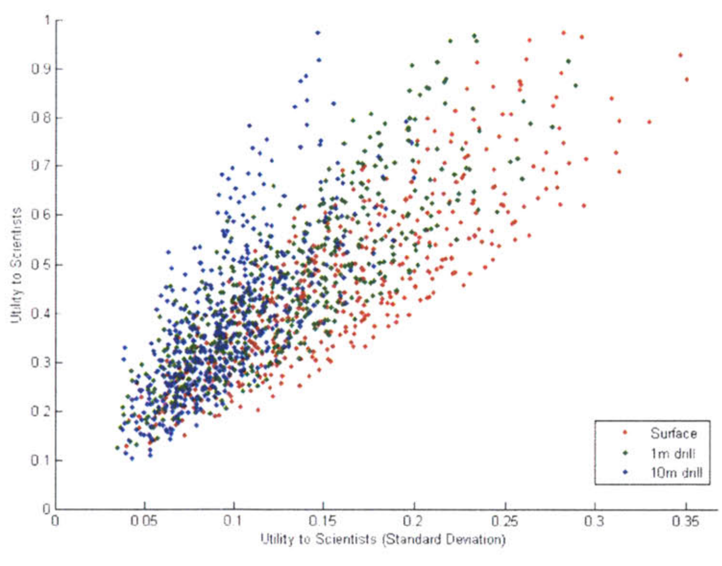



Figure 56 Impact of Drilling Depth Ambiguity on Science Value Assessment

### 4.4.9. Step 9 – Convergence Criteria

A set number of three iteration rounds was chosen as convergence criteria for the study. This criteria was selected to adapt to the time available for the study, the availability of the panel of experts, and verified by final round interviews. At its third iteration, experts felt no more need to change their assessments as they believed to have reached a valid representation of their opinions.

Figure 57 and Figure 58 show two matrices of bar plots with the convergence history for the engineering and science panels respectively. Rows in each matrix represent the different property variables that have been probed. The vertical axis on each graph plots the coefficient of variation, that is, the observed standard deviation normalized by the mean value of the sample. Round number is shown on the x-axis of each graph. Areas of reducible ambiguity are represented by plots where the coefficient of variation is reduced significantly between rounds. For instance, the variability on science value associated with the maximum horizontal characteristic radius (traverse distance – HorizRad Max in Figure 58) shows a decrease in ambiguity of ~90% in ~3 rounds. Other measures, such as sample depth on the sample plot, reveal areas of irreducible ambiguity that could not be reduced by framework iterations.

Convergence information as shown by the plots is valuable information for decision-makers, regardless of whether they identify areas of reducible or irreducible ambiguity. By providing knowledge on reducible ambiguities, system architects improve their confidence on their models, and substantiate the rationale for their conclusions. In cases where areas of open debates are identified, the framework allowed system architects to be aware of areas of uncertain value, where further discussion or analysis is required. As discussed in the Descriptive Systems Architecting Management Framework Approach, these are areas where decision-makers could consider delaying investments or developments, waiting for ambiguities to reveal in the future. Once convergence is declared, system architects can use DB-SAF for the last piece of analysis - that is, the informed development of reccomendations to decision-makers, using descriptive guidelines and canonical forms of ambiguity mitigation as prescribed in SA-MF (Section 3.5).

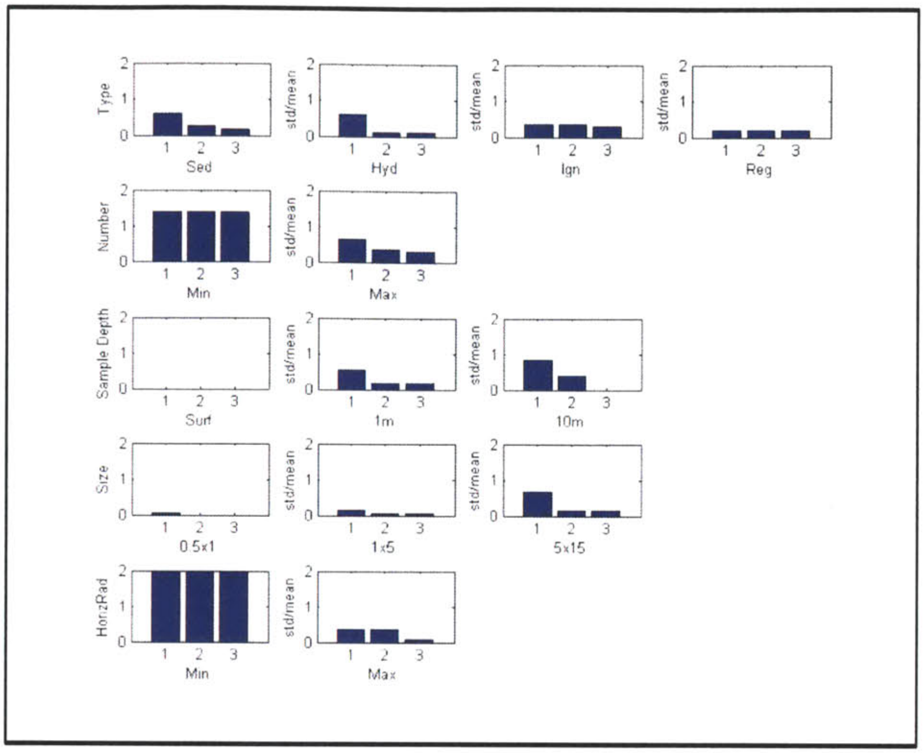



Figure 57 Engineering Panel - Round Progress Overview

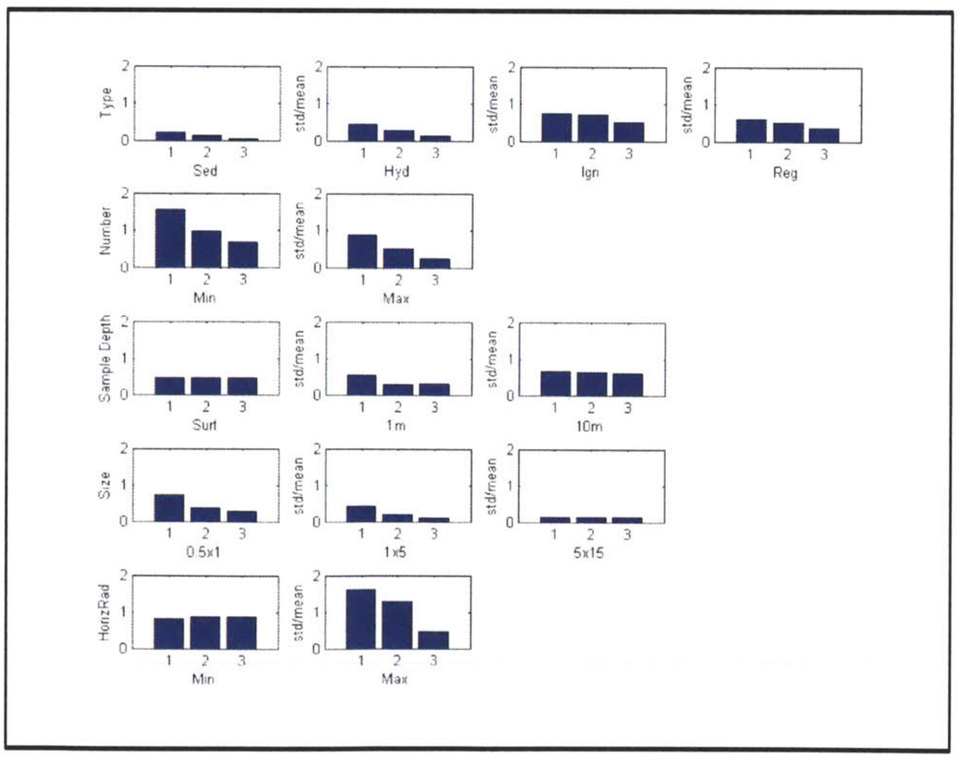



Figure 58 Science Panel - Round Progress Overview

### 4.4.10. Step 10 –Development of Recommendations

This chapter constitutes the documentation for the study. Further documentation and MATLAB code for the model developed for MSR is available in Appendix 9.2.

The following recommendations emerge from the analysis of results.

**Question 1: Does the current MSR architecture provide an efficient compromise between desired science returns and engineering complexity? (i.e. how far is it from ideal Pareto efficiency?)**

**Recommendation 1: If MSR will face tighter cost caps, cost-effective means to re-architect the campaign are to consider architectures de-scoped in the total number of retrieved samples while investing in sample recognition technology. Keep high operational flexibility in sample collection by maximizing sample diversity and maximizing horizontal mobility.**

***(Compromise and Buy Insurance in SA-MF)***

**Question 2: What other Pareto-efficient MSR architectures could be devised for different levels of total cost?**

**Recommendation 2: Consider a 2-element MSR campaign where Fetch functions are allocated to the Drilling and Caching rover to reduce foreseeable cost and schedule overruns by reduction of number of development projects. Initiate a study to evaluate the break-even point between extended operational lifetime of the caching rover and savings in development costs obtained by reduction in total number of development projects.**

***(Buy Insurance in SA-MF)***

**Question 3: What sample portfolio should MSR be designed for to maximize scientific returns?**

**Recommendation 3: Maximize scientific value delivered by maximizing the diversity in sample portfolio, collecting Sedimentary Materials, Hydrothermally & Low Temperature Altered Rocks, Igneous Rocks, Regolith, Dust and Atmospheric Gas within the MSR campaign.**

***(Consensus in SA-MF)***

**Question 4: What sample size should be MSR designed for optimal tradeoff between scientific returns and engineering complexity?**

> **Recommendation 4: Maintain baseline size specifications for collected samples (1.0cm D x 5.0cm H).**
>
> ***(Consensus in SA-MF)***

**Question 5: Is it worthwhile for MSR to accept the risk and invest in technology to retrieve samples beyond surface drilling (i.e. > 2.5cm)?**

> **Recommendation 5: Consider deferring 1-m and 10-m drilling payload implementations in the MSR architecture if faced with the need of meeting tighter cost caps. Invest in technology assessment areas to increase Technology Readiness Level and therefore reduce ambiguity surrounding complexity/science tradeoffs of deep drills.**
>
> ***(Defer Action in SA-MF)***

**Question 6: Is it worthwhile for MSR to accept the risk of extending horizontal mobility for distributed sample caching and in-situ science investigations?**

> **Recommendation 6: Consider extending horizontal mobility range for rover systems to enhance expected scientific value delivery and providing flexibility / added safety margins in landing site selection.**
>
> ***(Buy Insurance in SA-MF)***

## 4.5. Case Study Summary and Conclusions

The systems architecture of Mars Sample Return is a representative case study where ambiguities in upstream architecting processes have significant impact on downstream systems architecting definition processes. This case study assessed how ambiguities in defining science and engineering requirements impact campaign architecture on performance and cost metrics. Sections 4.1 and 4.2 provided an introduction and historical motivations to the study. Section 0 outlined specific objectives of the case study. Section 4.4 described the application of the Delphi-Based Systems Architecting Framework to the case of Mars Sample Return.

The study has been informed by a literature review (Step 1) and expert interviews at the NASA Jet Propulsion Laboratory. Following this preliminary phase, the analytic framework was developed. Step 2 describes Problem Formulation, including: identification of questions of interest, identification of goals, functional decomposition of the architecture, function-form mapping, architectural model description and model validation. Step 3 describes the international panels that have been formed for the analysis. The panels were composed of senior experts and high-level decision-makers involved with the current architectural baseline of the Mars Sample Return campaign. Steps 5 and 6 describes the design of the interview and the expert elicitation processes. Steps 7 and 8 discuss results, while Step 9 defines the convergence criteria used in this study. Step 10 develops recommendations based on the analysis.

The contribution of this case study to this thesis is to show the application of the Delphi-Based Systems Architecting Framework to a case with significant ambiguity in definition of subjective value metrics (such as science value and engineering complexity). The specific contribution of this study to MSR, in turn, is the identification of areas of ambiguity, the reduction of science and engineering ambiguities when appropriate, and the elicitation of areas of open debate and their impact in the systems architecting process such as sample weathering tresholds, having downstream impact on system design of the overall exploration and transportation infrastrucure. Recommendations to decision-makers are further contributions provided by the study. The hope of the author is to see Mars Sample Return campaign become a reality in the next thirty years.

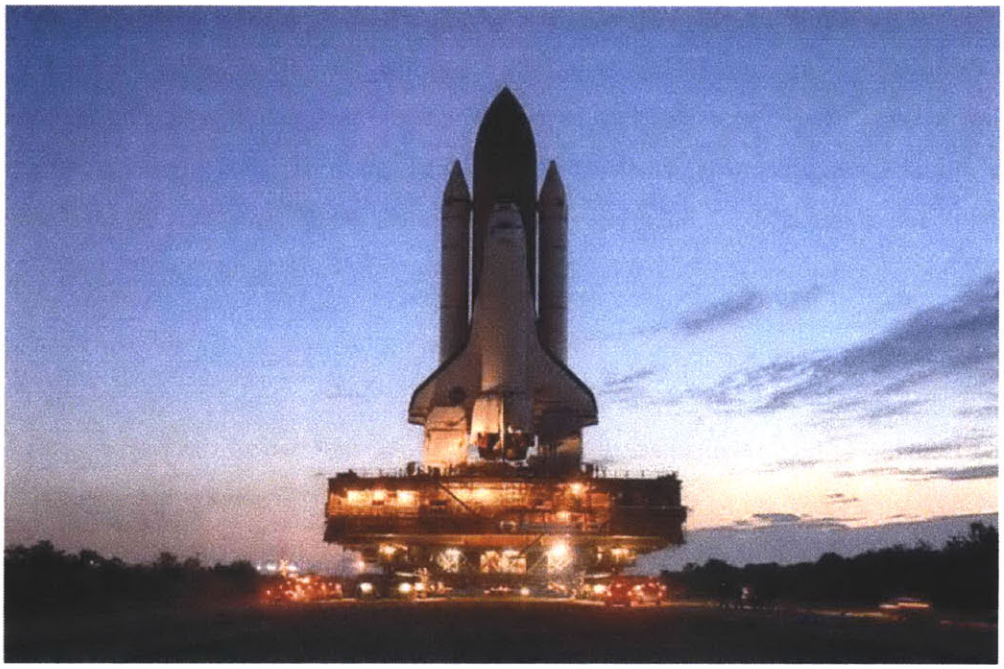
## 4.6. Acknowledgments

The author would like to extend his sincere gratitude to the following experts who contributed to the study: Robert Anderson (JPL), Pietro Baglioni (ESA), Diana Blaney (JPL), David Beaty (JPL), Luther Beegle (JPL), Charles Cockell (University of Edinburgh), Max Coleman (JPL), Joel Hurowitz (JPL), Richard Mattingly (JPL), Erik Nilsen (JPL), Robert Shishko (JPL), Charles Whetsel (JPL), Frances Westall (Centre National de la Recherche Scientique), and Ryan Woolley (JPL).

# Chapter 5 : Case Study 2 – Transportation Infrastructure for Future Human Spaceflight Missions Beyond Low Earth Orbit

*The shuttle tomorrow is truly like laying the last spike on the transcontinental railroad, only much more so. And whether or not we're going to see in in the next 10 or 20 years, there are people alive today who will see manufacturing in space from moon materials or from asteroids.*

— *Jerry Brown, Governor of California, 1977.*



*(image source: NASA)*

## 5.1. Introduction

Chapter 4 presented an analysis of Mars Sample Return (MSR) as a case study characterized by ambiguity within the underlying systems architecture. Recommendations have been developed on ambiguity-mitigating actions and alternative architectures for the program under analysis. Notwithstanding its challenges in meeting the budget and identifying effective science-engineering compromises, MSR is motivated by a crisp overarching objective: to retrieve sample from the Martian surface and return them to Earth.

Chapter 5 presents a more difficult engineering challenge featuring a higher degree of ambiguity: the architecture of in-space transportation infrastructure for human space exploration. Peculiar traits of this case study are ambiguity on objectives themselves ("What destination should we explore?") and on the definition of value-creating processes ("What is value for space exploration?"). The goal of this chapter is to demonstrate how the proposed DB-SAF framework can be used to mitigate this higher level of ambiguity – that is, ambiguity in the functional intent of the systems architecture.

This chapter presents an application of DB-SAF to a systems architecting analysis of the in-space transportation infrastructure for future human space exploration beyond Low Earth Orbit. The study has involved the formation of an international panel composed of 15 experts and high-level decision-makers from NASA, ESA, academia and industry. Experts have been engaged in three rounds of interviews each, for a total of 45 interviews and approximately 90 hours total of expert elicitation. Experts contributed to the study in anonymous form. Those of whom agreed to identify their participation are acknowledged at the end of the chapter – while specific contributions remaining anonymous as per the framework that has been developed. Data has been successively processed and integrated with a systems architecting engineering model for enumeration, evaluation and identification of architectures of interest. Internal validation has been achieved by comparing model-generated system architectures and past conceptual studies by NASA. The analysis is focused on characterization and mitigation of multi-domain ambiguities affecting this case.

The chapter is structured as follows. Section 5.2 provides motivations and historical context, framing the case study as relevant to the human spaceflight program of the first half of the XXI century. Section 5.3 describes the specific objectives of this case study discussing their relevance to the general objectives of this thesis. Section 5.4 describes the implementation of the Delphi-Based Systems Architecting Framework, and provides an overview of the underlying engineering model. Case study – specific results are discussed in Section 5.4.9. Recommendations are formulated for consideration of decision-makers concerned the development of the future in-space infrastructure for human exploration. Section 5.5 closes the chapter, summarizing findings and drawing conclusions from the case study.

## 5.2. Motivations and Context

While writing this thesis, NASA is called to charter a path for its future plans for human exploration. In 2004, President Bush started the Constellation Program with the ambitious plan of returning astronauts to the surface of the Moon (NASA 2004). Following six years of development and a cumulative investment of $9B billion USD (Chang 2010), a Presidential panel was chartered with the goal of assessing the status of the US Human Spaceflight Program and provide recommendations to the White House for future development of the American manned spaceflight program (the "Augustine Committee") (NASA 2009). The Committee found the US human spaceflight program to be "*on an unsustainable trajectory <...> perpetuating the perilous practice of pursuing goals that do not match allocated resources*" (NASA 2009). Following this review, the Obama Administration cancelled Constellation and the programs cancelled therein, such as the Ares I and Ares V launch vehicles (Connolly 2006). Eventually, in July 2011 the Space Shuttle completed its last flight and transitioned to its decommissioning phase, marking the end of an era in human spaceflight (Chang 2011).

Since 2010, the design of a man-rated transportation system has been a primary concern for NASA. Several teams within the Agency and industry in the US were called to assess alternative designs for a heavy lift launch vehicle (Braukus and Harrington 2010). Academia has also been involved in these studies. One instance was an independent analysis by the MIT Space Systems Architecture group that considered 192 launch vehicle architectures and possible launch vehicle family developments including a "super" heavy lift launch vehicle baseline (Aliakbargolkar, Wicht et al. 2011). In September 2011, NASA announced the development of the Space Launch System (SLS) as the next generation launch vehicle for future human exploration (NASA 2011). While most efforts have been focused on the development of the launch system, little efforts seems to have been spent upfront (at least in the public domain) on the definition of objectives and goals of the human spaceflight program. Stakeholders do not share a unified vision on what constitutes "value" for the exploration enterprise. Unclear goals translate into an uncertain need for a launch capability for future missions – therefore posing ambiguities on the definition of requirements for SLS and on the in-orbit exploration infrastructure.

Ambiguity is a double-edged sword in space exploration : stakeholders have variegate perspectives on the intrisic value of space exploration. Contrasting views on upside opportunities and downside consequences associated with space exploration can be identified in the literature on the role of space exploration in the world economy, policy and science. Debates generate both reducible and irreducible ambiguities, that must be mitigated to define a robust architecture for future space exploration infrastructure. Policy robustness is a key characteristic system architects need to consider to ensure steady value delivery to stakeholders (MIT and Draper 2005).

The *financial context* plays a significant role in setting objectives and constraints for space exploration. Its influences varies significantly depending on the aggregate stakeholders' value-at-risk attitude. NASA is a government entity funded through non-defense domestic discretionary spending. The annual appropriation process has adverse effect on NASA long term planning of exploration activities, as discretionary funding is perhaps the spending category most susceptible to overall budget restrictions in economic downturns (Auerbach 2008). Sustainability (Rebentisch, Crawley et al. 2005; Cameron, Crawley et al. 2008) and policy robustness (MIT and Draper 2005) are therefore primary concerns of risk-averse stakehoders. On the other hand, risk-taker stakeholders perceive exploration as an opportunity for the creation of a space economy, based on in-situ resource explotation funded by private investments

(Casini 2010). The overall influence of the financial environment on space exploration (the equivalent of a social welfare function in economics (Coleman 1966)) is therefore a weighted average of these perspectives - among others - subject to time-evolving ambiguity on weights ("which stakeholders are more important to consider in setting requirements?") and perspectives ("what is value in space exploration?"). The debate is further complicated as stakeholders have different views on what destinations should be targeted as first steps for human exploration; the Augustine Report provides an in-depth discussion of these issues (NASA 2009).

*Policy guidance* is a second primary driver of exploration. US space policy is subject to potential changes every 2 years (a Congressional mandate), 4 years (a one-term Presidential mandate) and 8 years (a two-term Presidential mandate). Exogenous influences contributing to reducible and irreducible ambiguity include – among others - the debate on international cooperation in space exploration (Peter 2006), the European Space Agency's *juste retour* principle in planning and managing programs and industrial procurement (Bonnet and Manno 1994), congressional pork barrel policy in the US (Johnson-Freese 2004) and the debate on US export control regulation on space programs (Blount 2008).

Lastly, the role of *science* has been a pivotal point of debate since the beginning of the human spaceflight program. One side of the space community believes that science is the primary *raison d'être* of space exploration - in a 2005 statement on NASA's Vision for Space Exploration, the American Astronomical Society stated that "Exploration without science is tourism" (Society 2005). Other stakeholders argue that robotic missions should be preferred over human missions, as the former accomplish science goals more easily and satisfactorily (Spudis 1999) at a fraction of the cost. This view is opposed to those who believe that humans are enablers of science (Pfarr, Calabrese et al. 2006). Astronauts have unique characteristics that differentiate them from robots, such as dexterity and the ability to change plans and adapt in real time. Human presence on a space mission allows plans to change and be flexible to unexpected discoveries, while allowing the execution of complex experiments in real-time (White and Averner 2001). Other stakeholders in turn support the societal role of human exploration (Huntress 2003), believing that exploring is an innate desire of humankind. From this perspective, science is regarded as a complement to human exploration, and not as a primary goal.

This overview showed a variety of perspectives on the definition on human spaceflight and surveyed the literature for sources of ambiguities surrounding the architecture of the exploration. The characterization and mitigation of those ambiguities is of paramount importance for effective definition of the architecture of the in-orbit transportation infrastructure for future human exploration. The goal of this chapter, therefore, is to show how DB-SAF can be effectively applied for this purpose, in the case of in-orbit infrastructure where objectives and goals are (yet) not clearly defined by. The study features inputs from fifteen experts including high-level decision-makers from NASA and ESA. While individual contributions remain anonymous, the names of those who agreed to identify their participations are gratefully acknowledged at the end of the chapter.

## 5.3. Specific Objectives

Section 5.2 provided motivations and context for the case study, laying out the ground for the analysis. This section describes specific objectives being pursued by the case study, and discusses their mapping to the general objectives of the thesis. This study looks at a case with unclear and strongly ambiguously defined objectives for future human space exploration – the elicitation of perceived needs, as per the ontological analysis of Section 3.1. The analysis achieves this goal by meeting the following objectives:

- Characterize and identify reducible and irreducible ambiguities in the definition of the architecture for in-orbit transportation infrastructure. Characterize the debate on value definition for an in-orbit transportation infrastructure as defined by representative decision-makers;
- Enumerate possible requirements sets for the human space transportation infrastructure and evaluate them according to representative stakeholders' value propositions;
- Identify requirement sets of interest for further analysis by system architects by achieving Pareto-efficient compromises between exploration, science and policy needs and goals, as measured by a set of subjective stakeholder value metrics informed by interviews to representative decision-makers.
- Enumerate feasible architectures for the human space transportation infrastructure complying with requirement sets of interest. Evaluate architectures according to proxy metrics for performance, cost, schedule and technical risk;
- Develop recommendations to decision-makers by identifying system architectures of interest for additional analysis.

## 5.4. Application of the Framework

### 5.4.1. Step 1 – Literature Review

The literature in human spaceflight mission architectures is very rich, as several proposals and mission architectures were studied in the last fifty years. A very comprehensive archive of this literature is available online at the Human Space Exploration Library maintained by Developspace Inc. (Developspace 2012). The main references considered in this thesis are the major efforts starting from 2000 with particular emphasis on NASA and MIT human spaceflight studies. In response to the Vision for Space Exploration, MIT and Draper Labs. conducted a Concept Exploration and Refinement

Exploration Systems Architecture Study for a broad tradespace exploration of Moon and Mars mission architectures (MIT and Draper 2005). Successively to this study, NASA developed an Exploration Systems Architecture Study (ESAS) to enact the Vision for Space Exploration laid out by the Bush Administration with the Constellation Program (NASA 2004; NASA 2005). The ESAS architecture was conceived and developed as a precursor program for future manned exploration of Mars. In the meantime, the NASA Johnson Space Center led conceptual design efforts in refining a Design Reference Architecture for a human Mars mission. This culminated in 2009 with the publication of Design Reference Architecture 5.0, which represents to date the most updated version in the public domain of NASA's approach for human Mars exploration (Drake 2009). Several other concepts for Mars exploration have been developed; their comprehensive overview is out of the scopes of this thesis. A major re-analysis of the Constellation Program occurred with the formation of a Presidential Committee in 2009 called by the Obama Administration and led by former Lockheed Martin CEO Norm Augustine. The Augustine Report laid out the idea of a "flexible path" for the future human spaceflight program, with an evolutionary approach for early value delivery to stakeholders and to phase program spending to reduce expenditure with respect to the original Constellation Program (NASA 2009). In 2010, the Obama Administration called for a new course for NASA's exploration program, eventually directing the Agency towards studies for an initial human mission to a Near Earth Asteroid. A Human Architecture Team (HAT, former Human Exploration Framework Team - HEFT) was formed by the agency to study human missions on NEAs. While HAT's work is still ongoing and no final report has been drafted at the time of writing of this thesis, preliminary findings can be found in NASA presentations available in the public domain (NASA 2010; Culbert 2011).

### 5.4.2. Step 2 – Problem Formulation

#### *5.4.2.1. Identification of questions of interest*

Given the current degree of ambiguity on the direction of the human spaceflight program (as of Q1 2012), this case study aims to address the following questions to inform requirements definition and highlight areas of interest for further conceptual study and definition of the systems architecture of the array of possible missions of interest for the next step in the human spaceflight program. In particular, this case study is focused on the architecture of the in-space transportation infrastructure required for future human exploration beyond Low Earth Orbit. Questions of interest include:

- What destinations should we consider pursuing for the US human exploration program of the next thirty years?

- What types of mission (orbit / surface / short stay / long stay) should we consider as effective compromise between exploration value, science and policy return?
- What are the main tradeoffs in exploration value, science return and policy return in architecting the in-space transportation infrastructure for human exploration? How do these metrics affect the architecting process as evaluated by performance, cost and risk metrics, and what is the impact of ambiguity in this context?

#### *5.4.2.2. Goals identification*

Stakeholder goals for the architecture of the in-space transportation infrastructure are not always clear and ambiguously defined. As the rationale for human space exploration is fairly diverse within stakeholders, there is no crisply defined goal on which stakeholders agree. Cameron proposed a value flow mapping approach for stakeholder analysis, which he applied to the case of human exploration to identify priorities within multiple stakeholder needs, modeled as stakeholder value flows (Cameron, Crawley et al. 2008). For the purposes of this thesis, we will consider a subset of the main Key Supporting Objectives (KSO) for human space exploration defined by the Global Exploration Roadmap (GER) of the International Space Exploration Coordination Group (ISECG 2011) relevant to the in-space transportation infrastructure architecture:

- Extend Human Presence [KSO 1]
- Develop Exploration Technologies and Capabilities [KSO 2]
- Perform Science to Support Human Exploration [KSO 3]
- Stimulate Economic Expansion [KSO 4]
- Perform Space, Earth, and Applied Science [KSO 5]
- Engage the Public in Exploration [KSO 6]

The Global Exploration Roadmap derives objectives from these goals, however, it does not provide rationale on how these objectives are linked to each other and how should they be prioritized in the program. For instance, boil-off control and in-situ resource utilization are both objectives mapped to KSO 2 in GER; however, a comprehensive assessment of technology investment is required to identify interactions and synergies between technology programs. A focused study on technology investment is out of the scopes of this thesis but is an interesting area of future research in support of decision-making in space exploration. This thesis instead is inspired by this problem to identify associated main trends and trade-offs, and analyze ambiguity in stakeholders evaluation (as elicited by expert panels) of different architectures for the infrastructure.

### 5.4.2.3. Functional decomposition

Functions are form-neutral statements derived from the goals as expressed by stakeholders. The in-space transportation infrastructure has been modeled with the following functional decomposition:

- Providing Habitation to astronauts at all phases during the <u>length</u> of the mission
- Transporting People and Cargo from Low Earth Orbit to the <u>Destination</u>

A detailed functional decomposition is shown in Figure 59. Note the two main ambiguities that have been underlined in the high-level functions above. The length of the mission is determined by the mission mode, the time spent at the destination and the choice of the destination itself. Destinations are part of the debate as their choice drives value delivery to exploration, science and policy stakeholders. While functions in the Mars Sample Return case study were crisply defined, this is not the case for this case. A higher degree of ambiguity is involved, as ambiguity includes the definition of the functinoal intent. The study of both ambiguity in the choice of a destination and assessment of mission length (as measured by total time of flight) is included in this chapter.

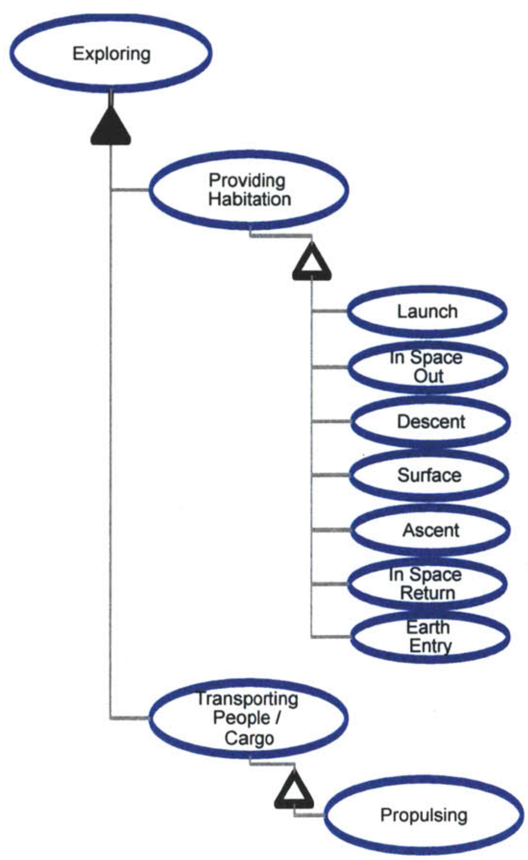



Figure 59 Functional Decomposition of the In-Space Transportation Infrastructure Architecture

### *5.4.2.4. Requirements enumeration*

Areas of potential ambiguity impacting definition of requirements include the following requirement variables:

- The choice of a **destination** (affecting value delivery to stakeholders in goals KSO 1, KSO 2, KSO 3, KSO 4, KSO 5, KSO 6)
- Characteristics associated with NEA destinations, such as **characteristic size** and **internal composition** (affecting value delivery to stakeholders in goals KSO 2, KSO 3, KSO 4, KSO 6)
- The **number of crew** in the mission (affecting value delivery to stakeholders in goals KSO 1, KSO 2, KSO 3, KSO 6)
- **Exploration time available at the destination** for exploration and science activities (affecting value delivery to stakeholders in goals KSO 1, KSO 2, KSO 3, KSO 4, KSO 5, KSO 6)
- The **time of flight of the mission, as a proxy measure of health risk** to astronauts due to exposure to the harsh radiation environment beyond Low Earth Orbit (affecting value delivery to stakeholders in goals KSO 1 and KSO 2)

Table 24 shows the requirements morphological matrix that has been formulated to study these ambiguities in more detail, by specific alternative options to be considered for each requirement variable. The size of the unconstrained tradespace of requirements in this formulation is of 21,600 possible requirement sets (unconstrained estimate). To allow comparison with existing architectural baselines, the analysis is focused on a representative mission portfolio comparable to existing NASA baselines such as the ones defined by HAT for NEAs, ESAS for the Moon, and DRA 5.0 for Mars, as outlined in the literature review in Section 5.4.1.

Table 25 shows logical constraints that have been formulated to generate this portfolio of representative missions.

Table 24 Requirements Morphological Matrix

| Requirement | Requirement Alternatives | | | | | | No# Alt. |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| *Destination* | Moon | Mars | Low Energy NEA | High Energy NEA | | | 4 |
| *Characteristic Destination Size* | <30m | 30m-100m | 100m-500m | 500m-1km | >1km | N/A (Dest. is not NEA) | 6 |
| *Characteristic Destination Composition* | Carb. | Silic. | Metallic | Other | N/A (Dest. is not NEA) | | 5 |
| *Number of Crew (# crew)* | 3 | 4 | 6 | | | | 3 |
| *Exploration Time at Destination (days)* | 7d | 21d | 30d | 180d | 550d | | 5 |
| *Maximum Total Mission Duration at Full-Scale Capability (years) - Health Risk Proxy* | <= 6m | 1y | 1.5y | 2y | 2.5y | 3y | 6 |
| *Mission Mode* | Orbit | Surface | | | | | 2 |
| | | | | | | Tot. Arch. | 21600 |

Table 25 Requirements Constraints

| Constraints |
|---|
| **Description** |
| IF Destination is Moon, OR IF Destination is Mars, AND Characteristic Destination Size IS NOT N/A OR Characteristic Destination Composition IS NOT N/A, THEN Architecture is Infeasible |
| IF Destination is Mars, AND (Exploration Time is 1m AND Total Mission Duration is NOT EQUAL TO 1y), OR (Exploration Time is 1.5y AND Total Mission Duration is NOT EQUAL TO 2.5y), THEN Architecture is Infeasible |
| If Maximum Total Mission Duration LESS than Exploration Time at Destination, THEN Architecture is Infeasible |
| If Mission Mode is Flyby and Exploration Time at Destination IS NOT 0d, THEN Architecture is Infeasible |

Value associated with requirement sets is defined by a multiplicative multi-attribute utility (MAU) function combining the following property variables:

- Total time of flight (as proxy for health risk)
- Exploration time at destination
- Delta V capability beyond Escape orbit
- Number of crew
- Destinations
- Object size (if destination is NEA)
- Object destination (if destination is NEA)

MAU functions are elicited by interviewing three panels of experts representing stakeholders for exploration, science and policy as discussed next in Section 5.4.3. Single-attribute utility functions are normalized functions where 0 is assumed as no value and 1 is assumed as full value delivered to stakeholders. Property variables are elicited using the score card method as discussed in Chapter 3. Equal complementary MAUA weights have been assumed for this analysis. Not all property variables are assumed equally relevant to the three panels. Table 26 shows the assumptions that have been used regarding relevance of each property variable for the science, exploration and policy panels that have been formed. These assumptions have been defined by an iterative verification process involving interviewees of all panels.

Table 26 Value attributes and their assumed relevance to expert panels

| Value Attributes and their Relevance to Expert Panels | Science Panel | Exploration Panel | Policy Panel |
|---|---|---|---|
| Total Time of Flight (Health Risk) | Less Relevant | Relevant | Relevant |
| Exploration Time at Destination | Relevant | Relevant | Relevant |
| Delta V Capability beyond Escape Orbit | Less Relevant | Relevant | Less Relevant |
| Number of Crew | Less Relevant | Relevant | Relevant |
| Destinations | Relevant | Relevant | Relevant |
| Object Size (if NEA) | Relevant | Less Relevant | Relevant |
| Object Composition (if NEA) | Relevant | Less Relevant | Less Relevant |

### *5.4.2.5. Function-form mapping*

Functions of the in-space transportation infrastructure architecture defined in Section 5.4.2.3 were mapped to elements of form as shown in Figure 60. The architecture is defined by a set of habitat elements and transportation elements. The mapping assumed here is not the only one possible for a transportation architecture. This mapping has been chosen to be compared with existing baselines such as DRA 5.0, Apollo, and NASA HAT studies. Mapping functions to a varying number of elements of form can be modeled as a set partitioning problem, which an avenue of interest for future research in this specific application. Different technology options for each element of form have been identified and organized in an architecting model, as described in the following discussion.

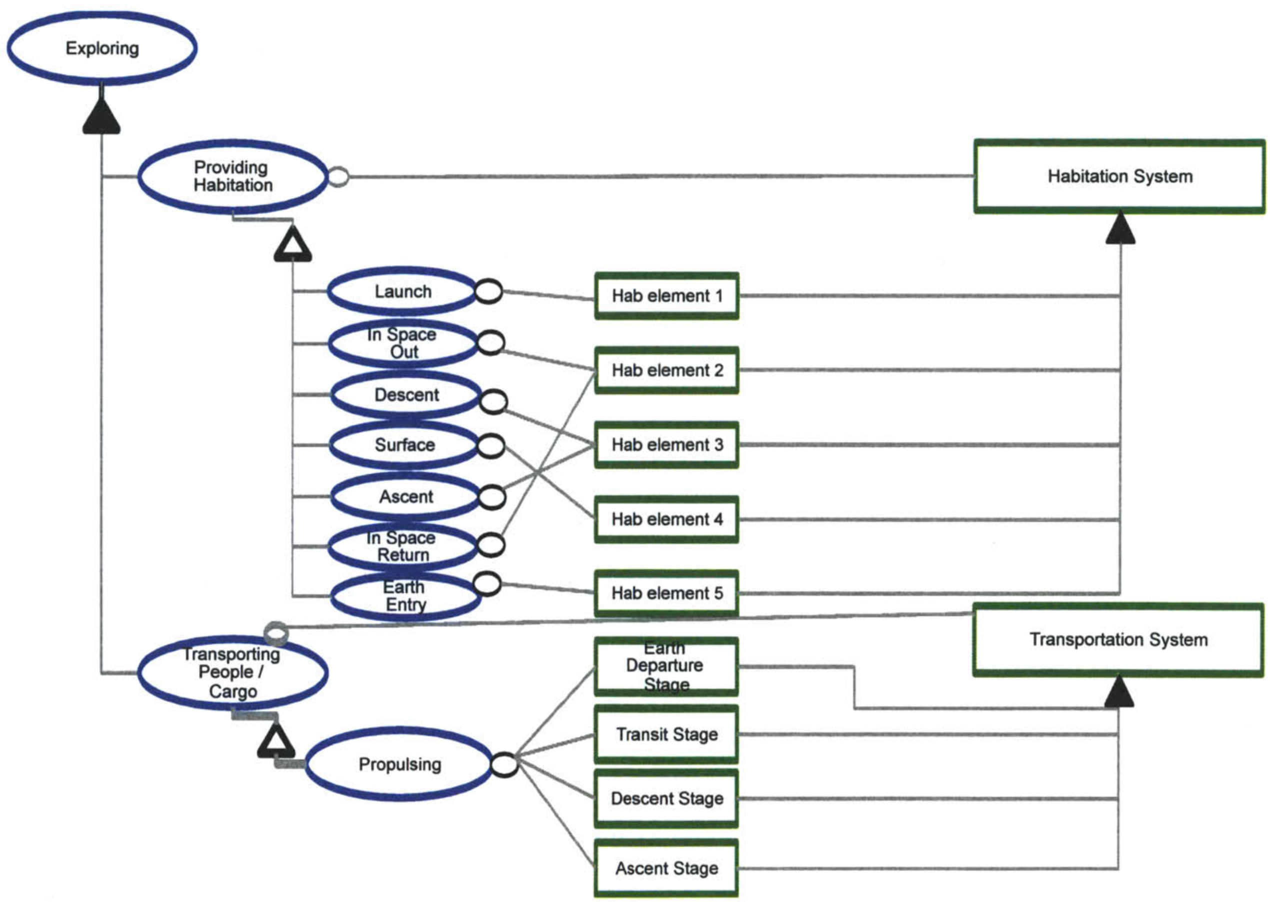



Figure 60 Function-Form Mapping of the In-Space Transportation Infrastructure Architecture

### 5.4.2.6. Architecting model

Architectural decisions and corresponding alternatives for the elements of form outlined in Section 5.4.2.5 is shown in Table 27. The design space is composed by 576 possible architectures per requirement set (constrained estimate). This results into an (unconstrained) integrated design space size of ~12.4m architectures.

The tradespace was explored with the following metrics:

- Exploration Value
- Science Return
- Policy Return
- Initial Mass in LEO (IMLEO)
- Architecture Risk Ranking (ARR)

*Architecture Risk Ranking* (ARR) is defined as an ordinal metric to rank architectures according to an overall risk assessment based on requirement-related (Table 28) and architectural-related (Table 29) risks. Risks are ranked with an ordinal scale from 1 (low risk) to 3 (high risk). Architectural risks are further distinguished by past flight heritage, as defined by proxy units of measure (such as landed mass for an aerocapture system). Architecture Risk Ranking is a normalized weighted sum of these two risk types. This discussion presents the analysis assuming equal weights.

The morphological matrix allows a comprehensive overview of available options for the infrastructure architecture. Cargo pre-deployment refers to the option of splitting crew and cargo payload in two separate flights; a cargo flight would be inserted in a low energy trajectory propelled by a Solar Electric Propulsion module, such as done in DRA 5.0 and in the NASA NEA mission as outlined by the HEFT architecting team – thereby reducing the overall architectural IMLEO. Propellant boil-off control is an additional option available for IMLEO reduction, by reducing boil-off of propellant – a critical feature in cryogenic propulsion systems such as those using $LOX/LH_2$. Boil-off control is an enabling technology for cryogenic propulsion in long-duration missions, when cryogenic propulsion stages are used only in later stages of the mission, therefore offsetting advantages in specific impulse with high mass penalties due to boil-off of propellant. In-Situ Resource Utilization (ISRU) and aerocapture are other possible technology investments to reduce IMLEO, at the cost of increased development costs and added operational and technical risks due to lacking operational experience, as measured by the architectural risk ranking metric as defined above. Other choices consider alternative propellant combinations for propulsion stages. The integrated assessment of this technology portfolio and possible requirement sets as elicited by stakeholders make this a comprehensive model of interest to assess ambiguity in the definition of the infrastructure architecture. The model assumes that elements in the infrastructure are always sized to allow future expansion to surface missions. For instance, in an orbit mission, the Earth Departure Stage would be sized to accommodate descent/ascent elements in future missions, designed for the same destination being considered in that architecture.

Table 27 Architectural Morphological Matrix

| Architectural Decision | Architectural Alternatives | | | No# Alt. |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| *Cargo Pre-Deployment via SEP Flight* | Yes | No | | 2 |
| *Propellant Boil-off Control* | Yes | No | | 2 |
| *In-Situ Resource Utilization* | Yes | No | | 2 |
| *Aerocapture* | Yes | No | | 2 |
| *Trans-Departure Injection Propellant Type* | LOX/LH2 | LOX/LCH4 | NTR | 3 |
| *Descent Propellant Type* | LOX/LH2 | LOX/LCH4 | | 2 |
| *Ascent Propellant Type* | LOX/LH2 | LOX/LCH4 | | 2 |
| *Trans-Earth Injection Propellant Type* | LOX/LH2 | LOX/LCH4 | NTR | 3 |
| | | | Tot. Arch. | 576 |

Table 28 Requirements Risk Elements

**Requirements Risk Elements**

| Destination | Risk |
|---|---|
| Moon | 1 |
| Mars | 3 |
| Venus | 3 |
| NEA Low Energy | 1 |
| NEA High Energy | 1 |

| Object Size (if NEA) | Risk |
|---|---|
| < 30 m | 1 |
| 30m-100m | 1 |
| 100m-500m | 1 |
| 500m-1km | 1 |
| > 1km | 1 |
| N/A | 1 |

| Object Composition (if NEA) | Risk |
|---|---|
| Carb | 1 |
| Silic | 1 |
| Metal | 1 |
| Other | 1 |
| N/A | 1 |

| Number of Crew | Risk |
|---|---|
| 1 crew | 3 |
| 2 crew | 3 |
| 3 crew | 2 |
| 4 crew | 2 |
| 5 crew | 1 |
| 6 crew | 1 |
| 7 crew | 1 |

| Time at Destination | Risk |
|---|---|
| 0d | 1 |
| 7d | 2 |
| 14d | 2 |
| 21d | 2 |
| 1m | 2 |
| 3m | 3 |
| 6m | 3 |
| 1y | 3 |
| 1.5y | 3 |

| Time of Flight | Risk |
|---|---|
| 6m | 1 |
| 1y | 2 |
| 1.5y | 2 |
| 2.0y | 3 |
| 2.5y | 3 |
| 3.0y | 3 |

| Mission Mode | Risk |
|---|---|
| Flyby | 1 |
| Sortie | 2 |
| Surface | 3 |

| Legend | |
|---|---|
| Low Risk | 1 |
| Moderate Risk | 2 |
| High Risk | 3 |

Table 29 Architectural Risk Elements

**Architectural Risk Elements**

| Boiloff Control | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Not Relevant | N.A. | N.A. |
| Yes | 2 | 2 |
| No | 1 | 1 |

| ISRU | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Not Relevant | N.A. | N.A. |
| Yes | 3 | 3 |
| No | 1 | 1 |

| Aerocapture | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Landed Mass [mt] | N.A. | N.A. |
| Yes | 2 | 2 |
| No | 1 | 1 |

| Transit Vehicle Propellant Type | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Prop. Mass [mt] | <= 120mt | > 120mt |
| LOX/LH2 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | N.A. | All |
| LOX/LCH4 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | <= 75mt | > 75mt |
| NTR | 2 | 3 |

| Ascent Vehicle Propellant Type | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Prop. Mass [mt] | <= 120mt | > 120mt |
| LOX/LH2 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | N.A. | All |
| LOX/LCH4 | 1 | 2 |

| Descent Vehicle Propellant Type | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Prop. Mass [mt] | <= 120mt | > 120mt |
| LOX/LH2 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | N.A. | All |
| LOX/LCH4 | 1 | 2 |

| TEI Vehicle Propellant Type | Proven Heritage | No Heritage |
|---|---|---|
| Heritage Unit: Prop. Mass [mt] | <= 110mt | > 110mt |
| LOX/LH2 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | N.A. | All |
| LOX/LCH4 | 1 | 2 |
| Heritage Unit: Prop. Mass [mt] | <= 75mt | > 75mt |
| NTR | 2 | 3 |

### *5.4.2.7. Model Validation*

The model has been validated by comparison with existing architectural baselines. The validation consisted in evaluating DRA 5.0, Apollo 11, and NASA HAT studies for NEA missions with the architecting model integrating exploration/science/policy value metrics, a performance/cost proxy metric (defined by IMLEO), and an ordinal architectural risk metric (the ARR defined in the previous section).

Table 30 Architectural Model Validation

| NASA Design Reference Architecture 5.0 | |
|---|---|
| Destination: | Mars |
| Characteristic Size: | N/A |
| Characteristic Composition: | N/A |
| Number of Crew: | 6 |
| Exploration Time at Destination: | ~1.5 years |
| Total Mission Duration: | ~2.5 years |
| Mission Mode: | Surface |
| Boiloff Control: | Yes |
| ISRU: | Yes |
| Aerocapture: | No |
| Transit Prop. Type: | NTR/LH2 |
| Ascent Prop. Type: | LOX/LCH4 |
| Descent Prop. Type: | LOX/LCH4 |
| TEI Prop. Type: | NTR/LH2 |
| Transit Vehicle Heritage | No Heritage |
| Ascent Vehicle Heritage | No Heritage |
| Descent Vehicle Heirtage | No Heritage |
| TEI Vehicle Heirtage | No Heritage |
| Total IMLEO: | 848.7mt |
| Model-generated Evaluations | |
| Exploration Value: | 1.00 |
| Science Value: | 1.00 |
| Policy Value: | 0.81 |
| Architectural Risk Ranking: | 0.88 |

| Apollo 11 | |
|---|---|
| Destination: | Moon |
| Characteristic Size: | N/A |
| Characteristic Composition: | N/A |
| Number of Crew: | 3 |
| Exploration Time at Destination: | ~3 days |
| Total Mission Duration: | ~8 days |
| Mission Mode: | Surface |
| Boiloff Control: | No |
| ISRU: | No |
| Aerocapture: | N/A |
| Transit Prop. Type: | LOX/LH2 |
| Ascent Prop. Type: | NTO/N2O4 |
| Descent Prop. Type: | NTO/N2O4 |
| TEI Prop. Type: | NTO/N2O4 |
| Transit Vehicle Heritage | Proven Heritage |
| Ascent Vehicle Heritage | Proven Heritage |
| Descent Vehicle Heirtage | Proven Heritage |
| TEI Vehicle Heirtage | Proven Heritage |
| Total IMLEO: | 1 x Saturn V (120mt) |
| Model-generated Evaluations | |
| Exploration Value: | 0.24 |
| Science Value: | 0.28 |
| Policy Value: | 0.15 |
| Architectural Risk Ranking: | 0.21 |

| Low Energy NEA (HAT 2000SG34) | |
|---|---|
| Destination: | NEA |
| Characteristic Size: | 300m |
| Characteristic Composition: | Carbonaceous |
| Number of Crew: | 4 |
| Exploration Time at Destination: | ~7 days |
| Total Mission Duration: | ~1 year |
| Mission Mode: | Surface |
| Boiloff Control: | No |
| ISRU: | No |
| Aerocapture: | N/A |
| Transit Prop. Type: | LOX/LH2 |
| Ascent Prop. Type: | N/A |
| Descent Prop. Type: | N/A |
| TEI Prop. Type: | NTO/N2O4 (MPCV) |
| Transit Vehicle Heritage | No Heritage |
| Ascent Vehicle Heritage | No Heritage |
| Descent Vehicle Heirtage | No Heritage |
| TEI Vehicle Heirtage | No Heritage |
| Total IMLEO: | 2 x 70mt SLS (140mt) |
| Model-generated Evaluations | |
| Exploration Value: | 0.35 |
| Science Value: | 0.5 |
| Policy Value: | 0.33 |
| Architectural Risk Ranking: | 0.33 |

| High Energy NEA (HAT 2008EV5) | |
|---|---|
| Destination: | NEA |
| Characteristic Size: | 300m |
| Characteristic Composition: | Carbonaceous |
| Number of Crew: | 4 |
| Exploration Time at Destination: | ~30 days |
| Total Mission Duration: | ~1.5 years |
| Mission Mode: | Surface |
| Boiloff Control: | No |
| ISRU: | No |
| Aerocapture: | N/A |
| Transit Prop. Type: | LOX/LH2 |
| Ascent Prop. Type: | N/A |
| Descent Prop. Type: | N/A |
| TEI Prop. Type: | NTO/N2O4 (MPCV) + LOX/LH2 |
| Transit Vehicle Heritage | No Heritage |
| Ascent Vehicle Heritage | No Heritage |
| Descent Vehicle Heirtage | No Heritage |
| TEI Vehicle Heirtage | No Heritage |
| Total IMLEO: | 3 x 70mt SLS (210mt) |
| Model-generated Evaluations | |
| Exploration Value: | 0.65 |
| Science Value: | 0.68 |
| Policy Value: | 0.69 |
| Architectural Risk Ranking: | 0.33 |

This chapter integrates DB-SAF with the IMLEO estimation model for in-space infrastructured developed by (Rudat and J.B. 2012) - who also validated IMLEO numbers using the same reference architectures used in this case study - and with the novel ARR model defined in Section 5.4.2.6. Table 30 shows model evaluations for exploration, science, policy value and ARR for reference architectures. Section 5.4.7 provides validation by locating said measures in the architectural tradespace and estimating their proximity from model-generated Pareto fronts.

### 5.4.3. Step 3 – Expert Panel Formation

Three expert panels were formed for this study, representing Exploration, Science and Policy stakeholders. All panels were composed by senior experts and decision makers involved in the architecture of the future human spaceflight infrastructure in the United States and in Europe. A total of 15 experts was used in the study, where each expert has been engaged in a three-round DB-SAF process. Expert contributions are provided in anonymous form, as agreed with individual experts. Some experts agreed to be identified as participants of the study; their participation is acknowledged at the end of the study. In no case contributions are explicitly attributed to any of those experts to protect their anonimity. Table 31 provides a synopsis on the composition of expert panels.

Table 31 Expert Panels Composition

| |
|---|
| **Exploration Panel** |
| 4 Senior Systems Architects & Decision Makers from NASA and ESA |
| 1 Professor from Academia (US) |
| **Science Panel** |
| 3 Professors from Academia (US) |
| 1 Senior Scientist from a US Research Institution |
| 1 Senior Scientist from a European Industrial Organization |
| **Policy Panel** |
| 2 Decision Makers from NASA and ESTEC |
| 1 Senior Expert (former President of a EU Space Agency) |
| 1 Senior Advisor from a US Research Institution |
| 1 Professor from Academia (US) |

### 5.4.4. Step 5 – Design of Interview

Interviews have been designed using the score card method, as discussed in Chapter 3. These have been deemed more appropriate for the property variables to be assessed in this case, rather than using formal utility function elicitation methods.

### 5.4.5. Step 6 – Elicitation of Expert Value Judgment

A total of 45 interviews were conducted to inform this study. Interviews were conducted in person, on VoIP teleconference and over the phone between September 2011 and February 2012.

### 5.4.6. Step 7 – Results Analysis

#### *5.4.6.1. Exploration Panel – Elicitation of Value Functions*

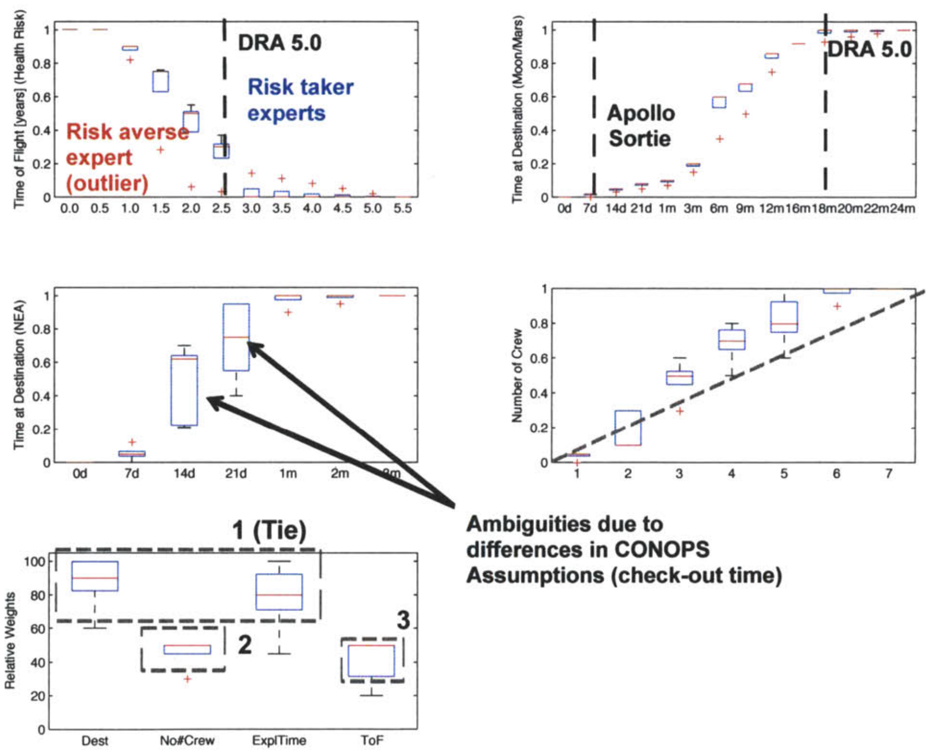



Figure 61 Exploration Panel - Round 3

Figure 61 shows results for the exploration panel at round 3. Experts in the exploration panel reached the best consensus among panels. The figure shows six plots, each one representing one value metric. The sixth pane shows weights assigned to value metrics in the aggregate multiplicative (hence nonlinear) MAUA formulation. The convention in all value metrics – in this and on science and policy panels as well - is that of *value-maximizing stakeholders*. A value 1 represents full stakeholder satisfaction, whereas a value 0 represents no stakeholder satisfaction. The following discussion reports an aggregate summary of expert opinions that have being gathered during three rounds of the elicitation procedure. Points of consensus and open debate are highlighted to identify areas of reducible and irreducible ambiguity.

*Time of Flight (as a proxy for health risk):* time of flight is a proxy of health risk as astronauts are more likely to face adverse conditions from exposure to the harsh radiation environment beyond the Van Allen Belts. In this metric, zero time of flight (no mission beyond LEO) represents no risk (maximum value to stakeholders). The *shape*, *gradient* and *horizontal offset* of the underlying curve is information of interest to system architects.

The *shape* and *gradient* on this curve depend on risk aversion of individual experts in the panel. Two opposing risk averse and risk taker perspectives surfaced rapidly in the panel. As risk takers were the majority in the panel, they are all included within 25th and 75th percentile of the box plots. A risk averse perspective was expressed by an outlier. Risk averse experts argue that safety is a key feature for any future mission of the human spaceflight program. the These experts argue that loss of human lives put the entire program at stake, and risk freezing the development of future missions - or even to threat the development of any mission at all - for several years after such accident. For risk averse experts , system architects need to minimize time of flight (for instance, by investing in breakthrough propulsion technology such as NTR) to reduce risks on astronaut health as induced by the environment. One expert expressed a risk taker view on this issue. Risk taker experts point at an excessive stress to safety as one of the main causes of cost growth and schedule slippage in past exploration programs. They argue that exploration as such is an inherently risky venture. Therefore, risk should be accepted as part of the program to enable sustainable access to new destinations in the Solar System. Risk taker experts make the point that the high safety record achieved by modern aviation is in part also due to lessons learnt during the last century, also at the cost of fatal accidents. They further point out to military systems, with different safety standards than analog civilian systems. It must be noted that six months were deemed safe by both risk taker and risk averse views due to legacy experience with the International Space Station (although this argument could be questioned, as the ISS does not operate in a deep space environment).

Health risk aversion is in part affected by underlying expert assumptions, as the radiation environment beyond the Van Allen Belts is mostly unknown. Humans have in fact no operational experience in a deep space environment. This aspect is considered by experts in setting the *horizontal offset* of the curve, which is driven by the time of flight for which they set value at zero. Most experts set their zero value between 2.5 and 3 years, as this is approximately the time of flight range for a conjunction-class human mission to Mars as specified by the NASA's Design Reference Architecture 5.0 (DRA 5.0), with two 6-month inbound and outbound trips, in addition to a ~550 days stay on the surface (Drake 2009). The assumption behind DRA 5.0 is the technology capability required for radiation protection of astronauts. Therefore, the horizontal offset of the curve is a function of technology available for radiation shielding and mitigation: experts expressed their opinions assuming the development of said enabling technology, including of a safe haven in pressurized habitats.

*Time at destination (Moon/Mars):* experts in the exploration panel were able to reach consensus on value associated to surface stay times on large planetary bodies. The underlying curve is an S-curve, where the shape and the gradient are representative of the marginal value increase or saturation associated with short stay and long stay durations. Experts agree that value associated to surface stay time has increasing marginal returns for short stays, as contribution to exploration value in the first days of exploration is significant, as new areas are explored and new operations initiated on the surface. The right-hand side of the curve shows diminishing marginal returns, meaning that the added value of an additional day on the surface when several months have already been spent there is low. The curve saturates at approximately 24 month stay durations for both Moon and Mars. While the policy panel required to make the distinction between these two cases, this was not the case for the exploration panel. Experts were specifically asked not to include orbital constraints in their assessment. For instance, some experts pointed out that not all surface stays are available on the Mars surface with current (chemical) propulsion technology, as return dates are constrained by the difference in Mars-Earth synodic periods. While this aspect is certainly true, experts were asked to think at value as decoupled by enabling technology. This was motivated by the intent to derive a curve to compare technologies in a second phase of the analysis. The analysis in this case would include enabling and future technologies allowing surface stay times not feasible under current technology assumptions.

*Time at destination (NEA):* time at NEA destinations was measured on a different time scale as agreed with experts. This was mainly driven by characteristic NEA object sizes, which are orders of magnitude smaller than planetary surfaces. Significant irreducible ambiguity is shown in this plot with value associated with 2-week and 3-week sorties to NEA surfaces. The open debate in this context can be traced to different assumptions by experts on time required for preparatory and system check-out operations. Experts argue that only a fraction of available days will be spent in value-delivering exploration activities, as initial days are spent in characterizing the NEA surface, assessing exploration risk, and verifying system operations to enable exploration. Such ambiguity could not be reduced in three rounds of iterations among experts, despite sharing expert opinions on those matters. Further discussion and drafting of a specification in this context with particular reference to detailed concepts of operations in the public domain of a NEA mission are advisable to reduce this ambiguity.

*Number of crew:* value associated with 1 to 3 crew is shown for completeness, although experts reached consensus in that 3 (same crew size as Apollo 11) is the minimum number of crew required for any exploration beyond LEO. Marginal value returns with added crew members is mostly linear as being proportional to the cumulative number of exploration operations that could be conducted on the mission. However, the curve suggests a slight bent at 4 crew, therefore showing diminishing marginal returns after that. This is in coherence with the current baseline of the Multi-Purpose Crew Exploration Vehicle (MPCV) as developed by NASA.

*Relative weights:* experts agree that the choice of a destination for exploration and time spent at the destination are primary drivers in the evaluation of exploration architecture. Relative ranking between the two is unclear, as the two boxplots mostly overlap, signaling a tie in this context. Number of crew is the second most relevant attribute from an exploration perspective. Time of flight is predominantly seen as the last factor of interest in evaluating architectures.

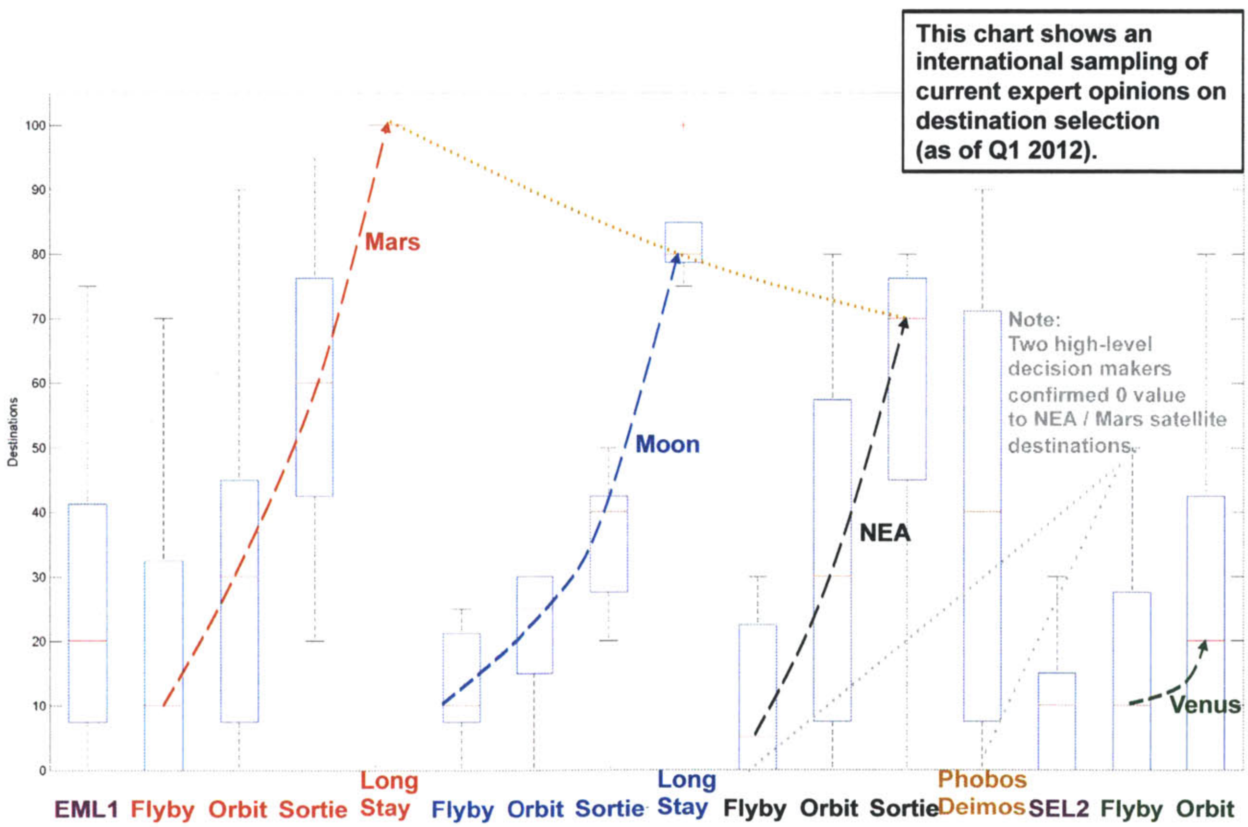



Figure 62 Exploration Panel - Destination choice - Round 3

*Destinations:* the choice of a destination shows the most irreducible ambiguity in all panels that have been involved in the study. The study was intentionally broad in this regard, and included non conventional destinations for a human spaceflight program such as Venus. The debate on destinations is found to be strongly opinionated – while in previous decisions experts were willing to compromise, DB-SAF iterations on destinations showed little room for negotiations. While evolutionary patterns between fly-by, orbit, sortie and long stay mission modes were widely recognized across the panel, the relative ranking between destinations was not. Furthermore, some destinations generated interest only with some experts - such as EML1 or Venus. Notably, NEAs are part of this category. While NASA's current efforts (as per 2012) are focused on the development of a mission to a NEA, not all experts agree on the validity of such approach. A detailed discussion of motivations for NASA to pursue a mission architecture to a Near Earth Asteroid instead of going to larger bodies in the Solar System such as Moon and Mars goes beyond the scopes of this thesis – the discussion being mainly driven by high development cost associated with surface landings not sustainable under current budget projections, and an evolutionary path to develop infrastructure capability over time for a manned mission to Mars as an end goal. A more in-depth discussion of this program architecture can be traced to the "Flexible Path" presented in the Augustine Report.

During the elicitation process, experts analyzed the choice of a first destination as a first step of in-orbit infrastructure development for a Flexible Path scenario. Arguments in favor or against each destination is discussed below.

**Earth-Moon Lagrange Point L1 (EML1)**

*Advantages:* EML1 is a natural staging point for in-orbit assembly operations; as stationary orbits on EML1 are stable, they mitigate operational risk associated with rendezvous and docking during assembly when compared to analog operations in Low Earth Orbit. Furthermore, the delta V associated with a LEO – EML1 burn is comparable to a LEO – Earth Escape burn, therefore enabling hardware commonality in Earth Departure Stages with other mission architectures beyond LEO for the same payload mass.

*Disadvantages:* EML1 has no exploration value per se. It does not qualify as a valuable destination, but only as an intermediate staging point.

**Mars Flyby**

*Advantages:* first step in gaining experience and developing capabilities for a surface mission to Mars.

*Disadvantages:* Exploration preparation does not justify a human flyby mission to Mars. Test human flyby missions were done to the Moon during the Apollo program (Apollo 8) due to the short transit time involved – 3 days instead of 1 year for a Mars conjunction-class flyby. Associated risks to human health and development costs do not justify such a mission.

**Mars Orbit**

*Advantages:* Enabling tele-operations of rovers and hoppers on the Martian surface with astronaut operators in orbit to reduce operational constraints due to communication lags in conventional robotic mission architectures. Enabling the development of a permanent outpost for remote sensing and other studies on the planet. First step in gaining experience and developing capabilities for a surface mission to Mars.

*Disadvantages:* Significant existing experience in Mars orbit missions with probes and orbiters and associated lower development costs make human orbiting platforms less attractive for science purposes.

**Mars Surface Sortie**

*Advantages:* First human presence on Mars. A 30 day stay allows a "short" Mars conjunction class to occur, therefore minimizing health risk induced by long-term stay on the first Mars surface mission.

*Disadvantages:* Low return on investment: 30 days surface time for a 1 year round trip. Requires the development of Entry Descent and Landing technologies for large payload masses (>10 mt), which is beyond current technological capabilities.

**Mars Surface Long Stay**

*Advantages:* Significant step forward in human space exploration. The panel agrees on the value of such a mission as the ultimate goal of the next thirty years of exploration. Architectures of long stay surface missions have been studied by NASA in several Design Reference Architectures. A long stay mission consists in a ~550 surface stay time (1.5 years) for a 1 year-long total travel time. The latest baseline is Design Reference Architecture 5.0, released in 2009.

*Disadvantages:* Long-stay missions require the development of several technologies that are not available today. Technologies include radiation protection/mitigation and enhancing capabilities such as in-situ resource utilization, boil-off control, aerobraking and entry descent and landing for large payload masses.

**Moon Flyby**

*Advantages:* Develops technology towards a future Moon surface landing, analogously to what has been done with Apollo 8.

*Disadvantages:* No real technological advancement, as this has been demonstrated multiple times in the past.

**Moon Orbit**

*Advantages:* Develops technology towards a future Moon surface landing. Enables remote sensing science on the Moon surface. Does not require development costs associated with man-rated descent/ascent systems.

*Disadvantages:* Remote sensing science has been demonstrated with unmanned probes with proven success.

**Moon Sortie**

*Advantages:* Precursor mission for Moon long stay and technology development for future Mars missions.

*Disadvantages:* Already demonstrated by Apollo program up to 7 days on the surface. Little hardware commonality on certain technology developments such as ISRU.

**Moon Long Stay**

*Advantages:* Development of a permanent lunar settlement capability on the lunar surface. Logical prosecution of the ISS experience. Enables lunar ISRU for in-orbit propellant depot supply and ISRU-based space resource commercialization (Sanders, Romig et al. 2005).

*Disadvantages:* Requires specific technologies not required or with large difference in requirements for systems required for Mars exploration. A commonality study is required to develop this insight in more detail.

**NEA Flyby**

*Advantages:* Develops technology towards a future NEA sortie.

*Disadvantages:* NEA mission very unlikely not to include surface rendezvous. NEA mission will most likely include interaction with NEA surface as well.

**NEA Orbit**

*Advantages:* Develops technology towards a future NEA sortie.

*Disadvantages:* Very unlikely to happen. NEA mission will most likely include interaction with NEA surface as well.

**NEA Sortie**

*Advantages:* Develops technology towards a future Mars mission at a fraction of the cost of a return to the Moon (i.e. Constellation program).

*Disadvantages:* Requires specific technologies not required or with large difference in requirements for systems required for Mars exploration. A commonality study is required to develop this insight in more detail.

**Phobos/Deimos**

*Advantages:* Enabling Mars proximity exploration without development of entry descent and landing systems required for Mars surface missions.

*Disadvantages:* Requires 1-year travel time and development of ascent/descent technology with higher cost than what is required for NEA missions.

**Sun-Earth L2 (SEL2)**

*Advantages:* On-orbit servicing of new generation observatories (such as the James Webb Space Telescope)

*Disadvantages:* No other purpose than on-orbit servicing.

**Venus Flyby**

*Advantages:* First mission to Venus. Technology preparation for future missions in the Solar System.

*Disadvantages:* Harsh radiation and thermal environment. Limited evolutionary path due to impossibility of conducting surface missions.

**Venus Orbit**

*Advantages:* First mission to Venus. Technology preparation. Remote sensing on Venusian surface.

*Disadvantages:* Harsh radiation and thermal environment. Limited evolutionary path due to impossibility of conducting surface missions.

*5.4.6.2. Exploration Panel – Main Highlights*

The following points emerge as main highlights from the development of representative value functions for the exploration panel:

- **Time at Destination (NEA):**
  - Exploration value between 14-days and 21-days is an irreducible ambiguity in different assumptions on Concept of Operations (CONOPS) – in particular due to different assumptions on time required for system check-out and testing before commitment to NEA surface operations.
  - The development of a common and open standard on a detailed mission CONOPS for NEA missions is recommended.
- **Destinations:**
  - Highest degree of irreducible ambiguity. At the same time, the panel ranked destinations as first most important attribute in the evaluation procedure.
  - Debate is highly opinionated, impossibility of reaching consensus.
  - Open debate on destination selection is highly recommended to reduce associated ambiguity within NASA and with international partners. Of particular interest is reduction of ambiguity on NEA mission architectures, which evaluation in terms of exploration panel appears bimodal, with experts giving high value to NEA missions versus experts giving zero value to NEA missions. Both parties did not agree in modifying their position at any point during the debate due to fundamental different value assumptions.

#### *5.4.6.3. Science Panel – Elicitation of Value Functions*

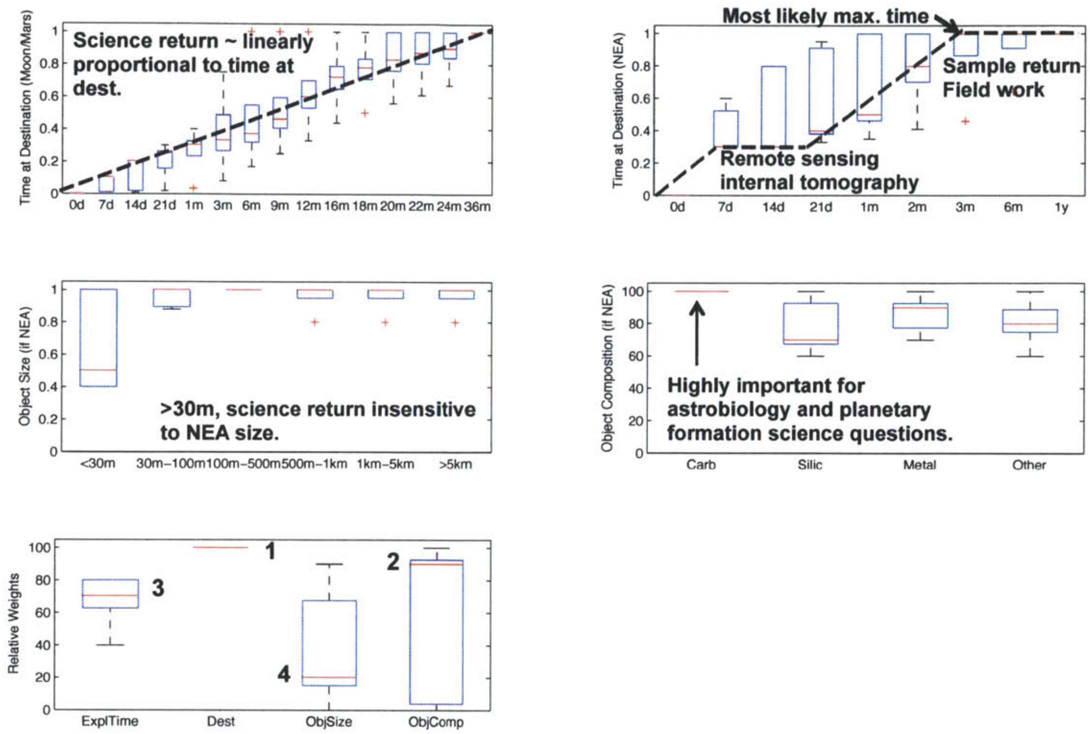



Figure 63 Science Panel - Round 3 Results

While the science panel on Mars Sample Return in Chapter 4 was the most affected by irreducible ambiguity among other panels, this was not the case in the human spaceflight case study. Science experts shared the opinion that science in a human spaceflight program is a complementary objective, certainly important but not primary. While scientists agree that unique advantages associated with astronaut presence are enablers and enhancers of science (in particular in sample return and geology field work), they also recognize that a vast majority of science objectives can be pursued with robotic platforms for a fraction of the cost of a human mission. With this assumption in mind, this discussion presents the rationale of experts in the science panel to provide a first-order science return evaluation of a given systems architecture.

The set of property variables of interest to scientists included exploration time at destination, NEA characteristic size and composition, and choice of a destination. A detailed discussion on those property variables follows.

*Time at destination (Moon/Mars):* A linear trend in science return emerged after three rounds of iterations: science return is perceived as proportional to exploration time at the destination. While this result is intuitive, this exercise provided validation to this statement.

*Time at destination (NEA):* Value associated with time on NEAs featured a double plateau, due to different types of science that could be done on that mission. Remote sensing and internal tomography of NEA interiors is possible via orbit operations, therefore representing early value delivering activities such a science program. Additional time spent (associated with NEA surface operations) increases value significantly by enabling sample return and geological field work activities. A maximum time of 3 months is foreseen on the surface for a first NEA mission.

*Object size (NEA):* for NEAs with a characteristic size greater than 30m (objects that would be too small pursuing for a human NEA mission), science value is insensitive to object size.

*Object composition (NEA):* object composition is an important discriminator in NEA selection for human missions. While all compositions are of interest to answer questions in planetary science, carbonaceous objects emerge as clear priorities due to their importance in answering relevant questions in astrobiology and planetary formation. Carbonaceous NEAs are samples of thermally unprocessed, pristine material from the origin of the Solar System (due to Calcium Aluminum inclusions – CAIs – analog to the ones found in meteorites as shown in Figure 64).

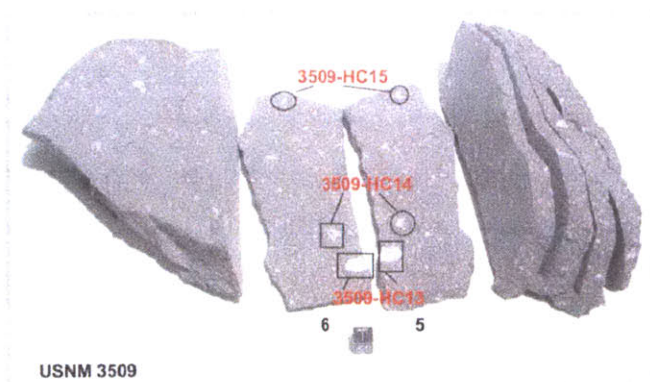



Figure 64 CAI inclusions in chondritic meteorites (image sorce: UMD)

*Relative weights:* the science panel followed a value-driven approach, where the choice of a destination was clearly recognized as the first priority in evaluation. Second to it object composition, although this opinion varied according to whether the expert in question was concerned with science related to NEA composition (such as geologists). Time spent at the destination emerged as third priority. Object size and time of flight tied as last priorities, as also shown in the discussion above.

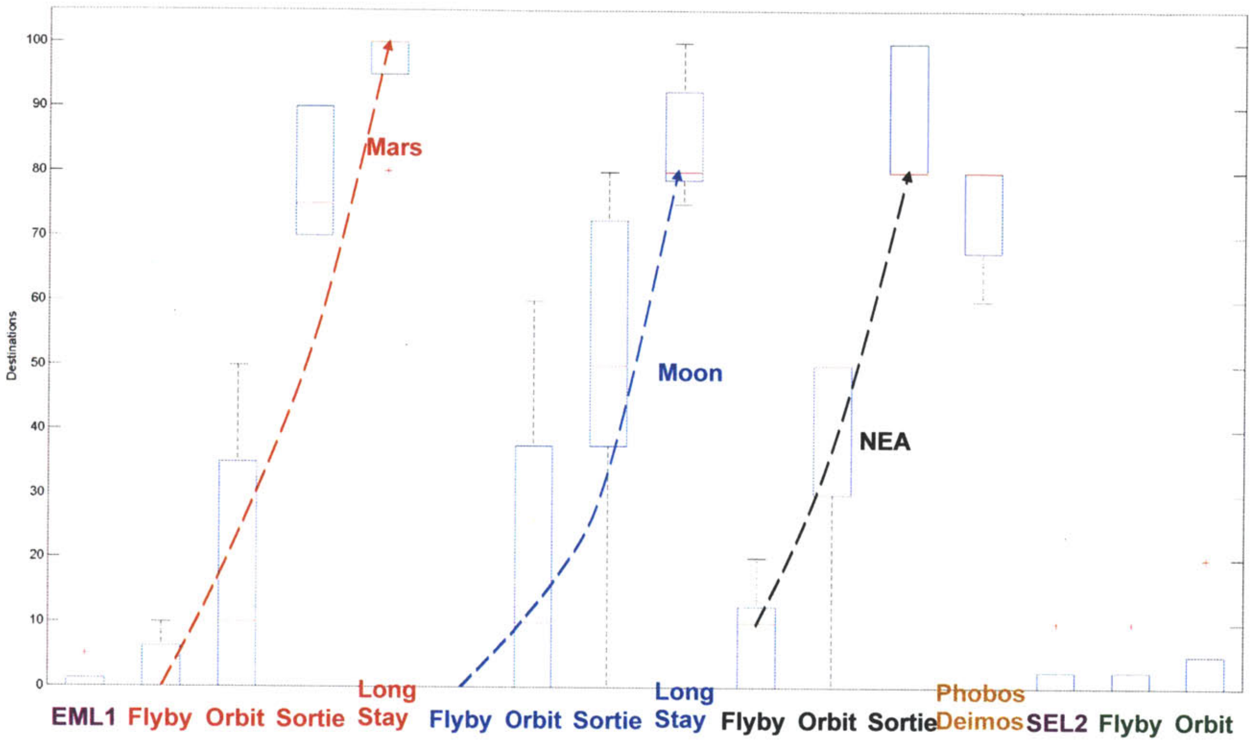



Figure 65 Science Panel - Destination Choice - Round 3

*Destinations:* the science panel showed more agreement in defining science value associated to destinations. Clear evolutionary trends are found in Mars, Moon and NEA missions. While NEA missions were considered of lower exploration value than Moon and Mars missions, a different judgment came from the science panel. As NEAs are valuable evidence to study planetary formation and the origin of the Solar System, they were retained by the panel of high science value. A similar argument holds for Phobos/Deimos. No or little science value was associated to EML1, SEL2 and Venus manned flyby/orbit missions, as neither of those benefit of humans as enablers of science.

### *5.4.6.4. Science Panel – Main Highlights*

- Humans are seen as enablers of certain science (such as sample return and geology field work) and evaluations calibrated accordingly.
- Carbonaceous are a privileged NEA category as they are samples of thermally unprocessed, pristine material answering questions on planetary formation and the history of the Solar System.

- Object composition is key for NEA mission selection. NEA size does not matter, unless looking at specific NEA science questions such as rubble pile versus onion shell theories for NEA internal composition, which can also be answered by use of tomography instruments.

### *5.4.6.5. Policy Panel – Elicitation of Value Functions*

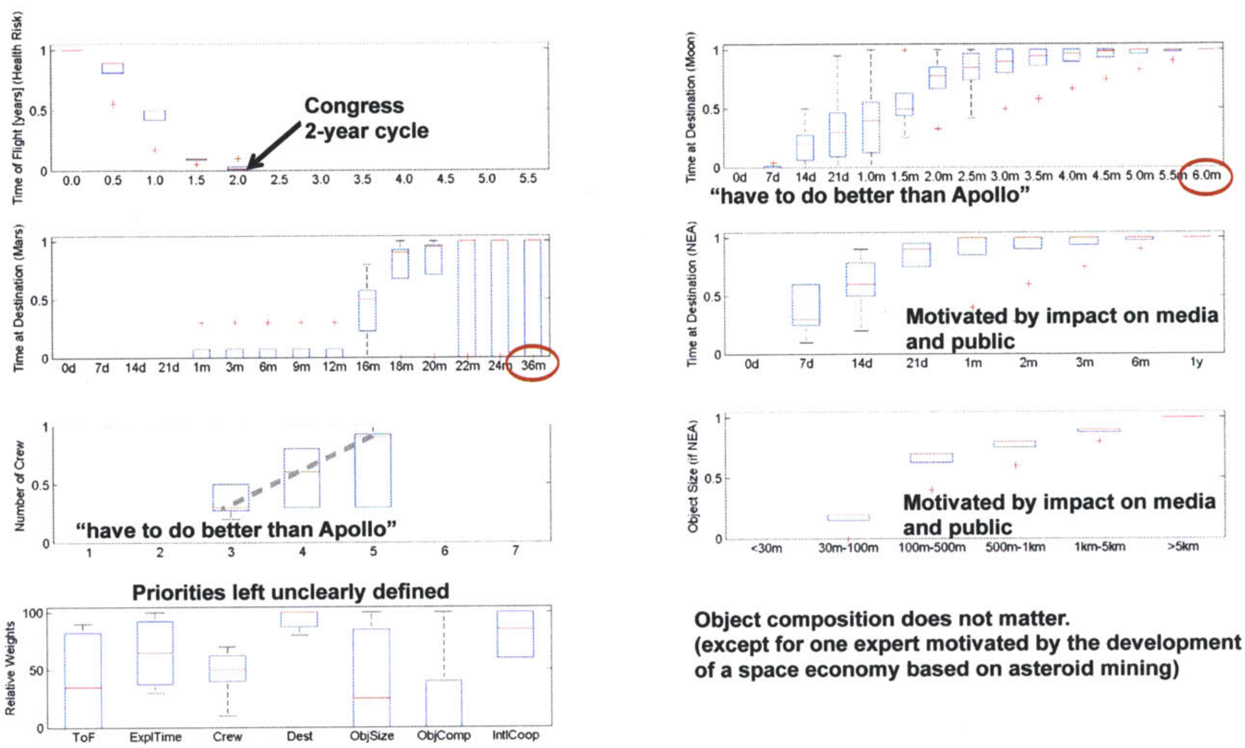



Figure 66 Policy Panel - Round 3 Results

The policy panel followed more qualitative logics and provided different types of motivations than the exploration and science panels in substantiating their answers. The following discussion overviews the rationale elicited by this panel.

*Total time of flight (as proxy for health risk):* time of flight was not seen only in light of technical constraints, but also considering policy constraints such as short-term policy return. Some policy experts in the panel motivated his answers based on the fact that US Congress changes in 2 year cycles, and a US President in 4 year (one term) and 8 year (two terms) cycles. Ambiguity on this value function could be effectively reduced in three iterations.

*Time at Destination (Moon):* the panel proposed to consider this measure separately for Moon, Mars and NEAs. For the Moon, the maximum was identified in 6 months for a lunar base settlement, in agreement with previous experience with the International Space Station. The trend over time follows a curve with diminishing marginal returns. However, ambiguity remains in defining clearly a point of diminishing marginal returns. Value was estimated as zero for a seven day Moon sortie, as experts stated the desire for new Moon programs to advance from the Apollo era and have an impact on media and the public opinion.

*Time at Destination (Mars):* a step-wise trend was identified by the panel, marking the difference between 30 day sortie and 550 sortie mission modes. The DRA 5.0 baseline for surface stay (~18 months) is on the point of diminishing marginal returns of the curve.

*Time at Destination (NEA):* a clear trend showing diminishing marginal returns was identified by the panel. Value saturates at 1 month of exploration, with substantial value delivery (> 50%) at 2 weeks of exploration. This was motivated as policy experts believe such a mission would have greater impact on media and the public in the short term rather than in the long term. This conclusion suggests to keep mission duration in the order of one month, in accordance with NASA studies on NEA missions conducted in 2012 by the Human Spaceflight Architecture Team (HAT).

*Number of Crew:* the panel took the Apollo program as a reference considering a crew range between 3 and 6 crew members, with a linear increase in value in this range.

*Object Size:* value increases proportionally to object size showing diminishing marginal returns. Object size is related to the impact on the media and the public associated with the mission. Note that *object composition* was deemed irrelevant by policy experts. An exception is made by experts advocating for the development of a space economy, who are therefore interested in NEA objects which composition suits the needs for the development of commercial ventures (such as asteroid mining activities).

*Relative Weights:* an unclear priority ranking was elicited by the panel. High irreducible ambiguity is due to the plurality of non reconcilable intents.

This last result implies the lack of strong leadership driving worldwide policy opinions. This is also confirmed by looking value judgment results associated with destinations.

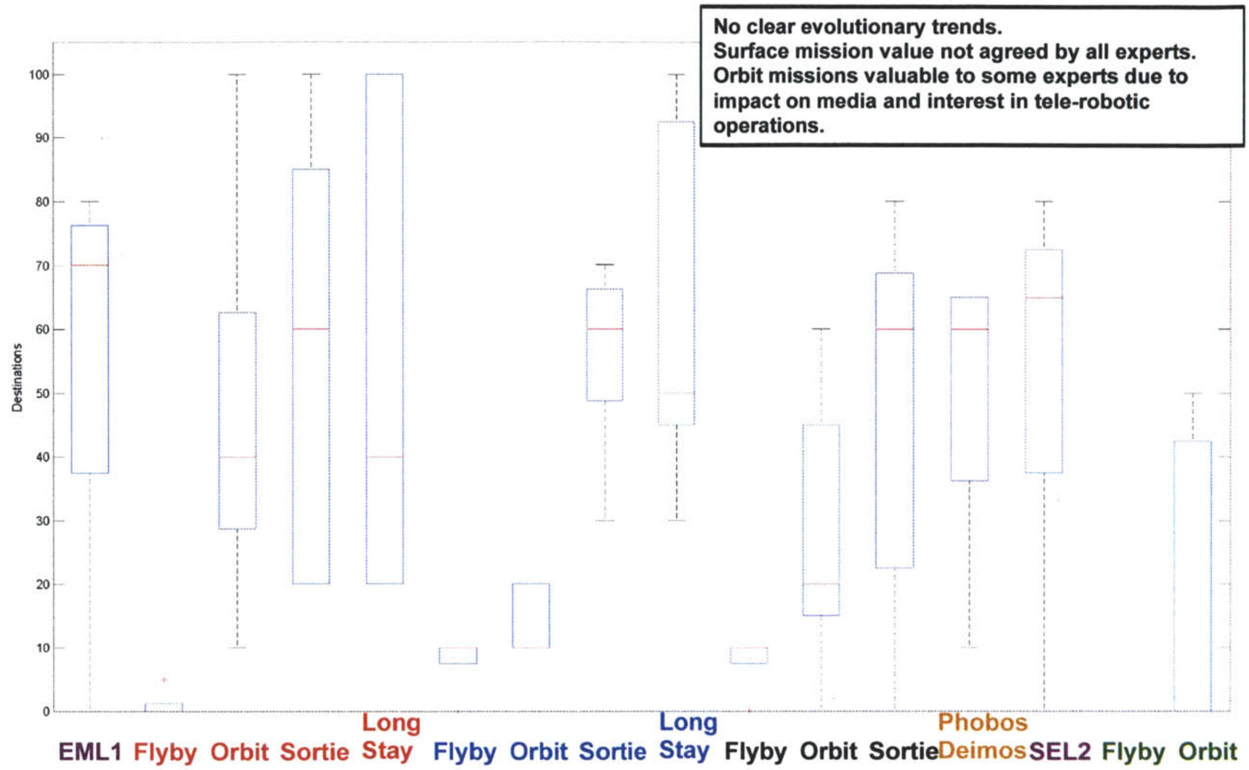



Figure 67 Policy Panel - Destination choice - Round 3

*Destinations:* this panel feature the greatest degree of irreducible ambiguity associated with destination across panels. No clear evolutionary trends were identified between missions modes (flyby, orbit, sortie and long stay). Value associated with surface missions was not agreed by experts; for instance, not all experts associated maximum value to a Mars surface mission as expressed by the vast majority of experts in the exploration and science panels. In some cases, orbit missions were deemed more valuable than surface missions as experts believed these alone deliver significant impact to the media and on public opinion, while enabling exploration opportunities provided by tele-robotic exploration on planetary surfaces – therefore mitigating communication lags.

### *5.4.6.6. Policy Panel – Main Highlights*

- No clear leadership or consensus emerging, which implies the need to bring concepts for further evaluation.
- Time scale arguments were based on impact on media and public opinion, and were based on coherence with possible political changes rather than scientific/engineering rationale, such as for instance using the following timescale of events:

- 2 years: Congress lifecycle
- 4 years: One-term President
- 8 years: Two-term President

- No evolutionary trends in destination choice was found between mission modes (flyby, orbit, sortie and surface long stay) as perceived by other panels.
- Orbit missions were deemed valuable by some policy experts for their impact on media and public opinion (such as in Apollo 8).

### 5.4.7. Step 8 – Aggregate Results Discussion

A first result of interest can be achieved with a first-order benefit-cost analysis of the in-space transportation infrastructure. In this context, a proxy for benefit is defined as the weighted average of median values delivered to expert panels (exploration, science, and policy) as measured in Round 3 of DB-SAF iterations. Weights represent decision-maker preferences to different panels, i.e. to different categories of experts – a sensitivity analysis to weights is conducted to assess robustness of the analysis. A proxy for cost is defined as the total delta V that the infrastructure needs to provide for a given destination / mission mode (for instance Moon Sortie, or Mars Long Stay). We neglect Venus in this analysis, as DB-SAF results have shown this choice was dominated in value in all panels by other destinations. Table 32 shows the input data for this analysis. Sensitivity analysis results to different panel weights are shown in Figure 68, Figure 69, Figure 70, and Figure 71.

Table 32 In-Space Transportation Infrastructure - Benefit-Cost Analysis - Input Data

| | Exploration Value (Median) | Science Value (Median) | Policy Value (Median) | Total delta V (km/s) |
|---|---|---|---|---|
| EML1 | 20 | 0 | 70 | 7600 |
| Mars Flyby | 10 | 0 | 0 | 11444 |
| Mars Orbit | 30 | 10 | 40 | 11444 |
| Mars Sortie | 60 | 75 | 60 | 17527 |
| Mars Long Stay | 100 | 100 | 40 | 17527 |
| Moon Flyby | 10 | 0 | 10 | 8450 |
| Moon Orbit | 25 | 10 | 10 | 8450 |
| Moon Sortie | 40 | 50 | 60 | 12404 |
| Moon Long Stay | 80 | 80 | 50 | 12404 |
| LoNEA Flyby | 5 | 10 | 10 | 6927 |
| LoNEA Orbit | 30 | 50 | 20 | 6927 |
| LoNEA Sortie | 70 | 80 | 60 | 9010 |
| HiNEA Flyby | 5 | 10 | 10 | 9892 |
| HiNEA Orbit | 30 | 50 | 20 | 9892 |
| HiNEA Sortie | 70 | 80 | 60 | 11975 |
| Phobos/Deimos | 40 | 80 | 60 | 11975 |
| SEL2 | 10 | 0 | 65 | 8200 |


Figure 68 Benefit-Cost Analysis Results - Equal Weights (33.33% Exploration, 33.33% Science, 33.33% Policy)

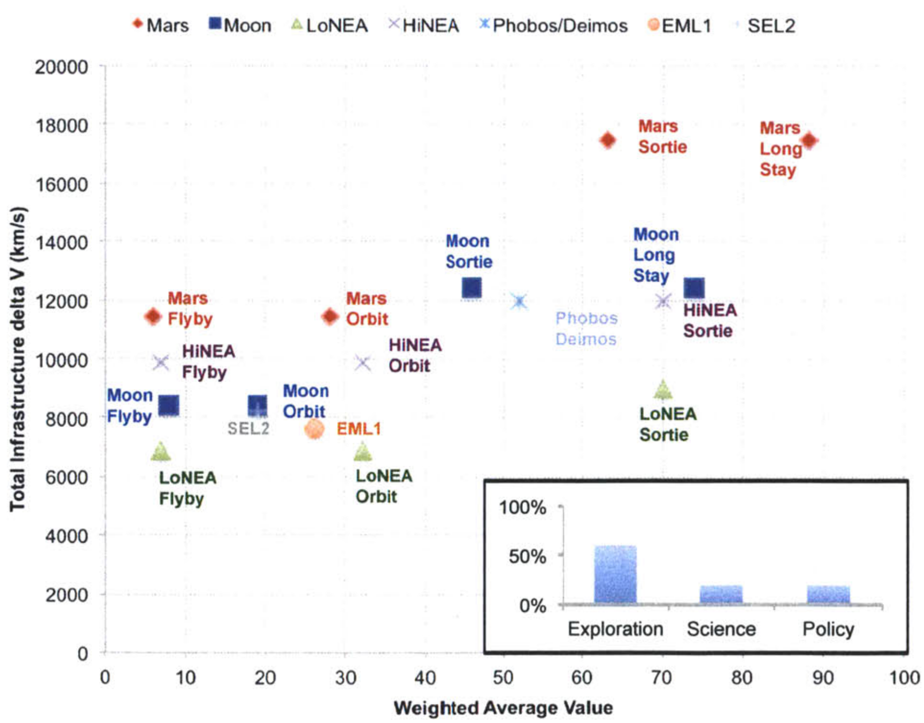



Figure 69 Benefit-Cost Analysis Results - Exploration Bias Scenario (60% Exploration, 20% Science, 20% Policy)

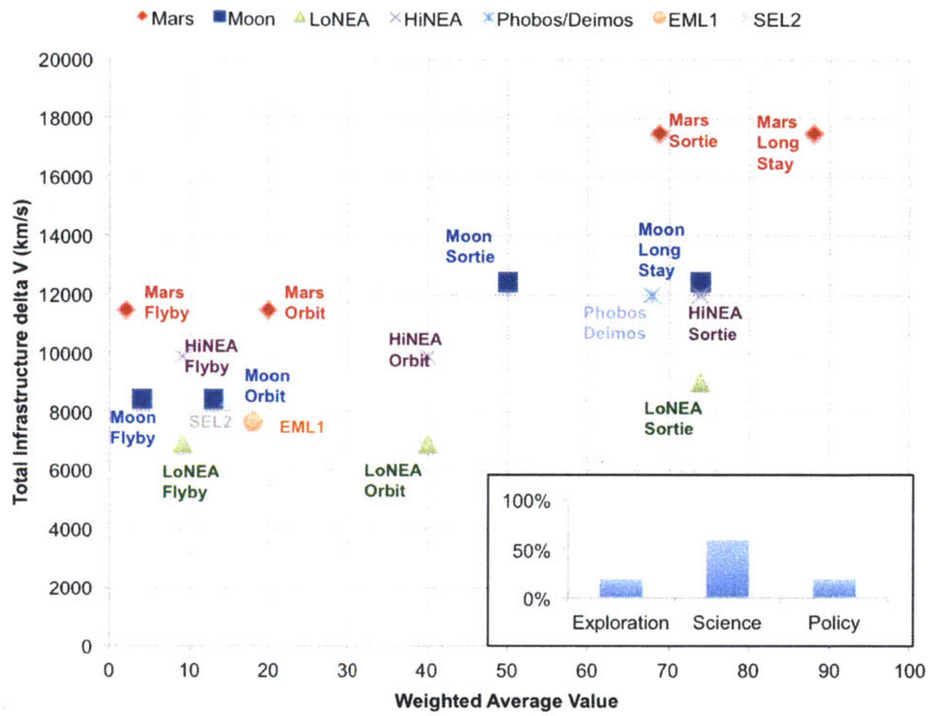



Figure 70 Benefit-Cost Analysis Results - Science Bias Scenario (20% Exploration, 60% Science, 20% Policy)

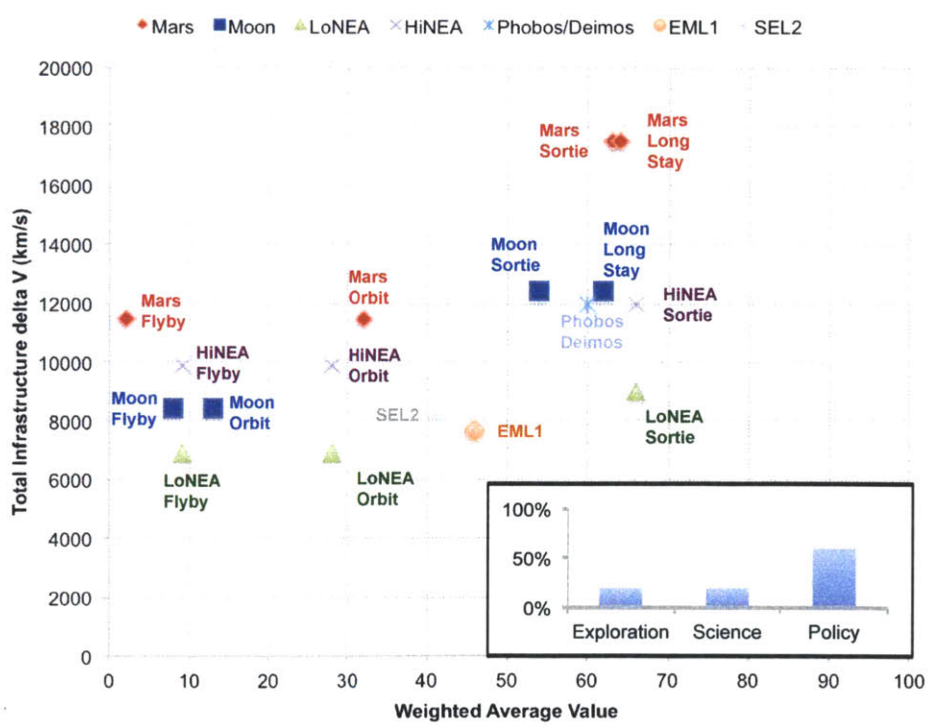



Figure 71 Benefit-Cost Analysis Results - Policy Bias Scenario (20% Exploration, 20% Science, 60% Policy)

The following results emerge from the first-order benefit/cost analysis shown in the abovementioned figures:

- NEA destinations are always on the Pareto front. Low-energy NEAs represent efficient benefit/cost tradeoffs being on the kick of the curve. This result is confirmed in all the scenarios considered in the sensitivity analysis.
- While high-energy NEAs are always dominated in a Pareto sense, they represent destinations of interest as they require higher capabilities in terms of delta V, better approaching energy requirements of future Mars missions.
- Value associated with mission duration and mission mode (flyby vs orbit vs sortie vs long stay) is moderately panel dependent. Said value is higher for exploration and science biased scenarios, for which longer durations are preferred. Value is lower in the policy-biased scenario, as policy experts showed preference for shorter mission durations for early value return within Presidential and Congressional mandates.
- Value associated with EML1 and SEL2 destinations is highly panel dependent. They show high value (close to the Pareto front) in the policy-biased scenario, as these destinations comply with current policy guidance (as of Q1 2012), and represent a gateway for future exploration as discussed previously. An exploration-biased assumption returns moderate value from these destinations, since technology development is enabled by these destinations (while having lower exploration value when compared to other alternatives). Value is low in a science-bias assumption, as EML1 and SEL2 are empty points in deep space, where no human-enabled science (such as sample return) can be performed.

We now perform design space exploration analysis integrating the requirements tradespace in Table 24 and the architectural tradespace in Table 27 and using the value functions defined by the exploration, science, and policy panels. Design baseline architectures described in Section 5.4.2.7 are used for model validation and comparison with existing studies. Figure 72 shows architectures grouped according to different destinations being pursued. Each quadrant represents the intersection between a value function as elicited from expert analysis, and proxy evaluation metrics for performance/cost - defined by IMLEO - and risk - defined by the ordinal ARR metric previously defined.

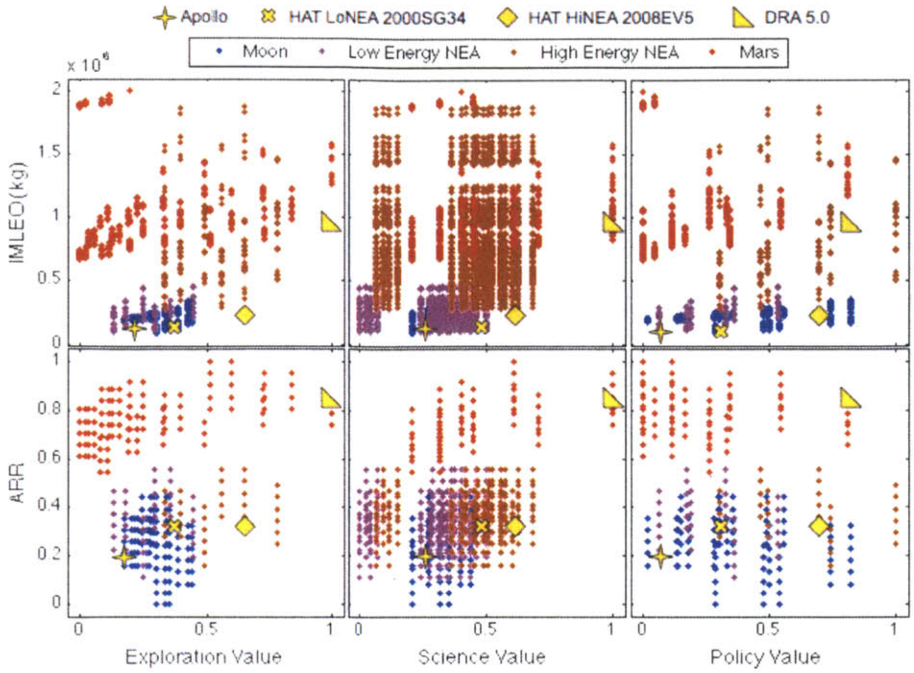



Figure 72 Architectural Design Space - Destination View

We considered architectures for which 0 < IMLEO < 2000mt. Architectures beyond the upper treshold are unrealistic, resulting from dominated combinations of architectural decisions. We can immediately verify that existing architectural baselines lay close to 2-dimensional Pareto fronts of the integrated design space, therefore providing confidence on validity of the architectural model. Several tradeoffs are represented: the multi-performance Pareto front shows the logical progression of increase in overall value between destinations. This discussion considers performance/value-maximizing, cost/risk-minimizing stakeholders, for whom therefore maximum exploration/science/policy value is desired (value 1.00), while minimizing IMLEO and ARR. Architectural tradeoffs are highlighted in the chart. For both exploration and science panels, ordinal rank on the IMLEO/Value Pareto fronts is as follows: Low Energy NEA / Moon (lowest value) → High Energy NEA → Mars (highest value). Low Energy NEA and Moon architectures are differentiated from an Architectural Risk Ranking standpoint, with Moon architectures features lowest risk due to prior operational experience represented by the Apollo program. Tradespace exploration from a policy perspective (third column in the figure) highlights the current stance of the human spaceflight political debate. Moon and NEA architectures are at different levels of the Pareto front, while Mars architectures stand back as dominated. This result is due to expert opinion elicitated in the policy panel, where several experts provided low score to Mars missions based on sustainability grounds due to perceived policy return / cost ratio of such mission, given current tight budget forecasts and policy directions. Moon and low energy NEA missions (comparable to the 2000SG34 NASA HAT baseline) are competing options in the low-IMLEO region of the Pareto front, as per the motivations discussed in Round 3 results of Exploration and Science Panels in Sections 5.4.6.1 - 5.4.6.4. This analysis does not intentionally suggest an "optimal" destination pursue. A global optimum is unachievable, as the expert elicitation identified non reconciliable, irreducible ambiguities within panels. While full consensus is not possible, efficient compromise is instead a possibility enabled by this analysis. Architectural analysis provides a transparent approach to characterize subjective value-based architectural tradeoffs and compare them with objective metrics such as IMLEO estimates and risk assessments such as done with the proposed ARR metric. Final selection is left to decision-makers, whom are called to express an aggregate judgment based on their relative weights between exploration, science, and policy considerations. An analytical alternative would be to formulate a "Super-stakeholder" utility function (analogous to social welfare functions in economics) representing decision-makers, and therefore providing an ordinal ranking of architectures by aggregating metrics in a single-objective function. However, this approach would bias the analysis towards a particular decision-maker's view and preference structure. An analytic approach further assumes acceptance of the axioms of rationality in decision-making such as maximization of expected value, which are seldom employed in complex decisions in the real-world where subjectivity (induced by ambiguity, irrationality and hidden agendas) is heavily involved. More importantly, such approach is prone to critiques as decision-making under ambiguity is a complex non-linear, discontinuous process. We prefer, instead, to show tradeoffs as they presented themselves during expert elicitation iterations, having removed reducible ambiguity and highlighted irreducible ambiguity in the debate using DB-SAF. The final decision is left therefore to decision-makers.

We consider now the scenario where NEAs are selected as first destinations of a Flexible Path architecture, in accordance to what is being currently pursued by NASA at the time of writing of this dissertation. We note on the side that while this architecture is the current program of record for future human spaceflight missions at NASA, it is affected by irreducible ambiguity in value associated to NEA destinations, with large dissent from several expert panel members involved as shown by the DB-SAF expert elicitation in previous sections. In this scenario, questions of interest include the selection of desired NEA properties such as *characteristic size* and *composition*. Figure 73 and Figure 74 show the design space grouped by object (NEA) size and composition, respectively.

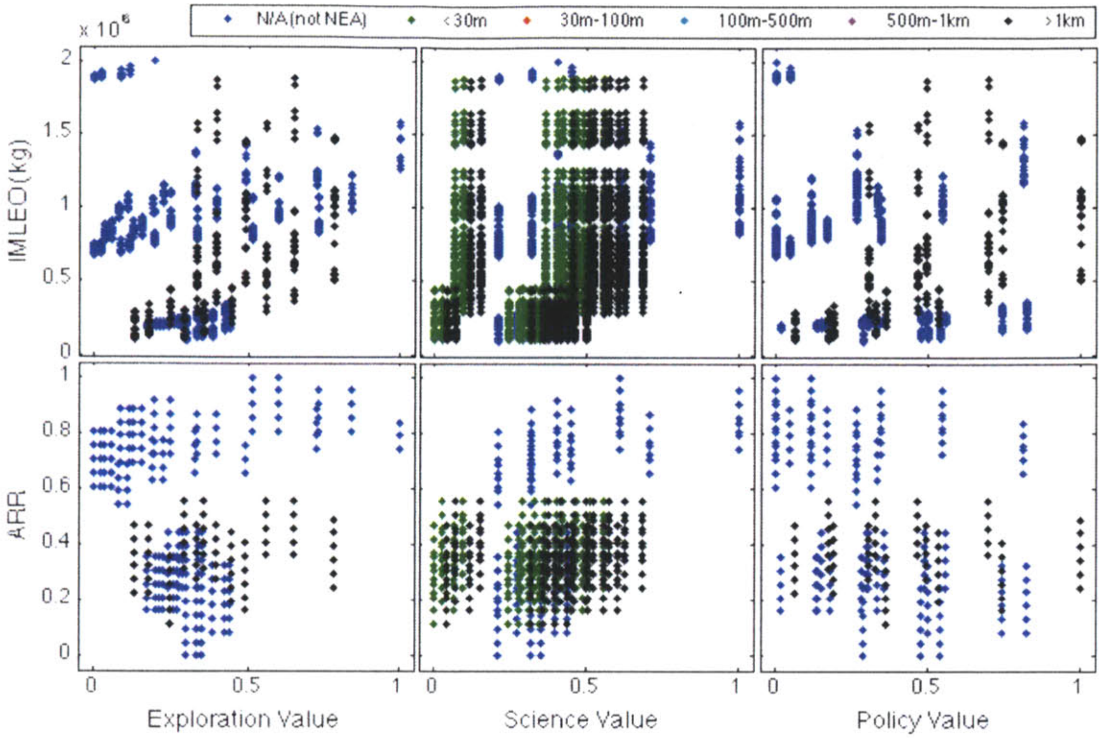



Figure 73 Architectural Design Space - Object Size View

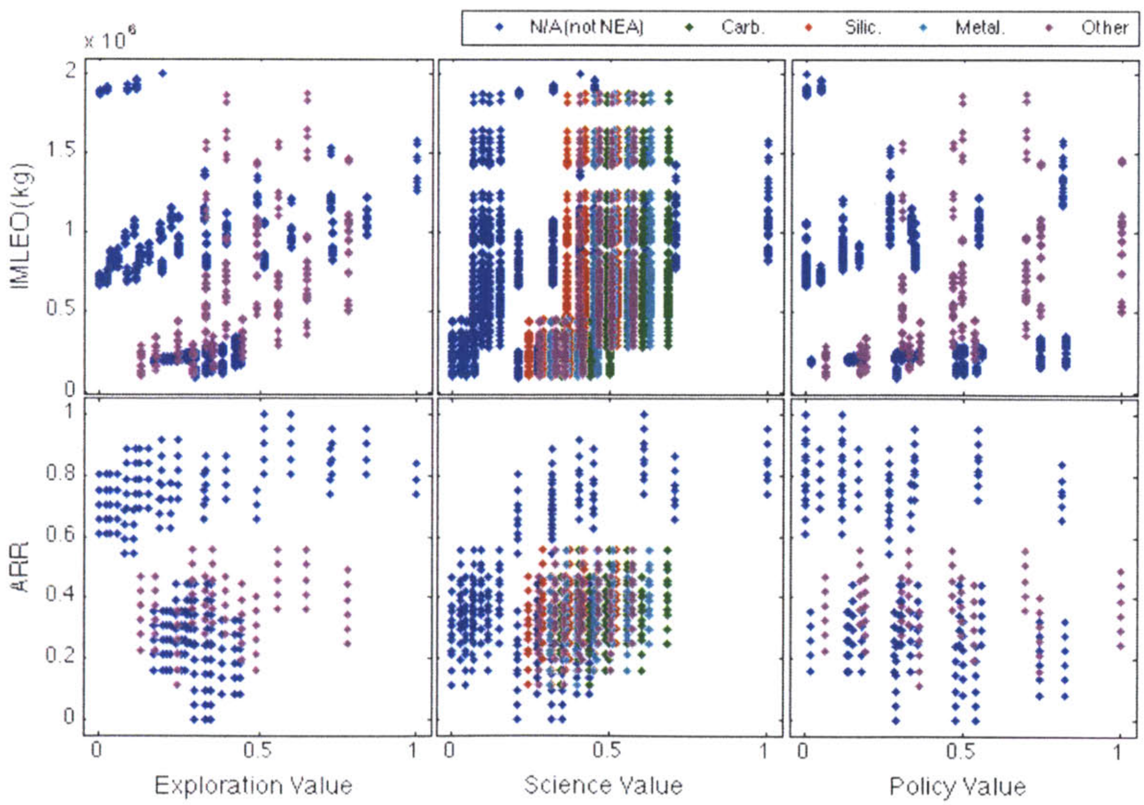



Figure 74 Architectural Design Space - Object Composition View

Both questions on size and composition have a clear indication from tradespace exploration. Carbonaceous NEAs dominate throughout the NEA design space, as also shown in previous discussion of DB-SAF panel results. This is mostly due to sinergies in astrobiology and geology questions that can be answered returning carbonaceous NEA samples on Earth. Value perception is insensitive to NEA characteristic size, with the exception of small sizes – which also lead to infeasible mission architectures due to impractical rendez-vous and docking operations with the celestial body. While both exploration and science panels gave initial indication of relevance of both requirement variables during DB-SAF iterations, ambiguity was quickly reduced to low sensitivity of exploration/science value to both variables – with more sensitivity expressed from the science panel. It must also be noted small NEAs are oftentime in fast rotation around their spin axis in unstable motions, while large NEAs are slow, stable rotating bodies – therefore representing a preferred choice from a CONOPS perspective. Lastly, ARR plots show that NEAs are middle ground in Architectural Risk Ranking in the design space, representing intermediate risk options between Moon (lowest ARR) and Mars (highest ARR) architectures.

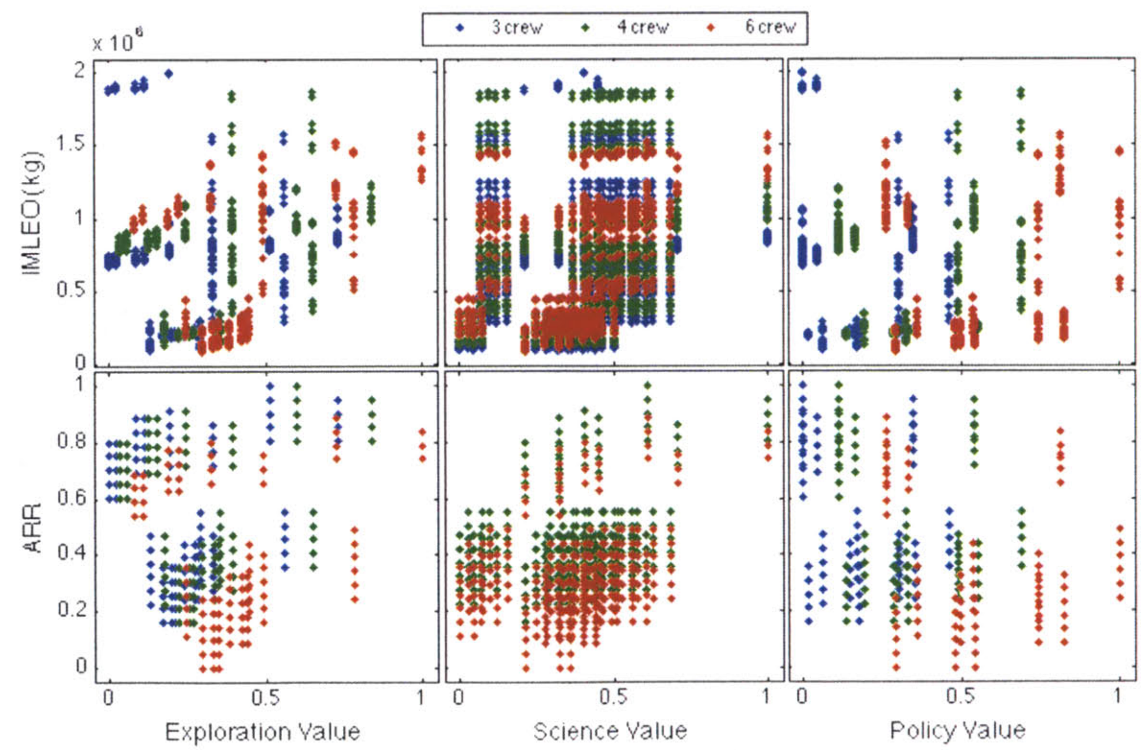



Figure 75 Architectural Design Space - # Crew View

Notwithstanding the choice of a destination, the determination of the *number of crew* is a critical decision in the architecture of the in-orbit transportation infrastructure. The proposed architecting model coupled with DB-SAF identifies the tradeoff between marginal increase in exploration/science/policy value associated with the addition of a crewmember to the architecture, associated with reduction of risk as measured by the ARR due to enhanced survivability of the crew during the mission. This is of particular interest for the sizing of future exploration vehicles such as NASA's Multi-Purpose Crew Vehicle (MPCV, Figure 76). MPCV sizing is a primary driver of the architecture infrastructure, as shown in the ambiguity impact analysis discussed later in this section.

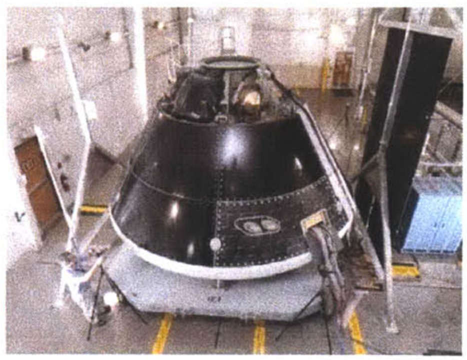


Figure 76 Multi Purpose Crew Vehicle (image source: Lockheed Martin)

Architectural tradeoffs associated with exploration time, time of flight and mission mode are directly related to the insights discussed for destination choices. Their detailed discussion goes beyond the scopes of this dissertation. However, for completeness, such plots are reported in Appendix 9.1 (Figure 108, Figure 109, and Figure 110 respectively).

We now resort to ambiguity impact analysis to identify areas of concern to decision-makers between irreducible ambiguities that have been identified in this study. We will consider both architectural tradespace metrics in this study, namely IMLEO and ARR. First we analyze ambiguity impact using a Design of Experiments, Main Effects analysis. Figure 77 shows the results of main effects analysis on IMLEO. Results show dominance of the choice of a destination as the primary effect impacting the systems architecture. This is a very important area of concern as previous sections discussed widespread irreducible ambiguity in this context. Choice of a number of crew is the second most impactful requirement decision, which however poses less of an issue given relatively low associated irreducible ambiguity. Ambiguity Impact Analysis on ARR (Figure 78) yields to analog results.

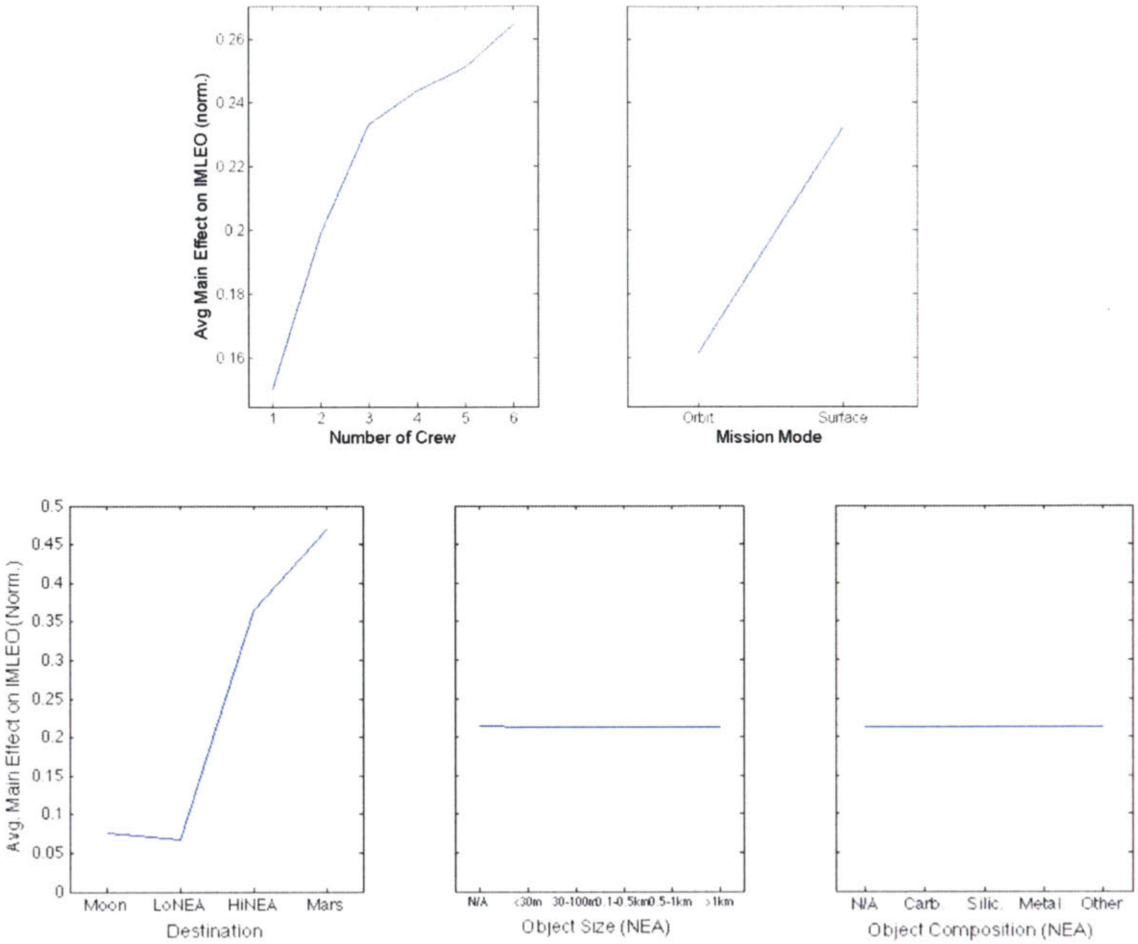
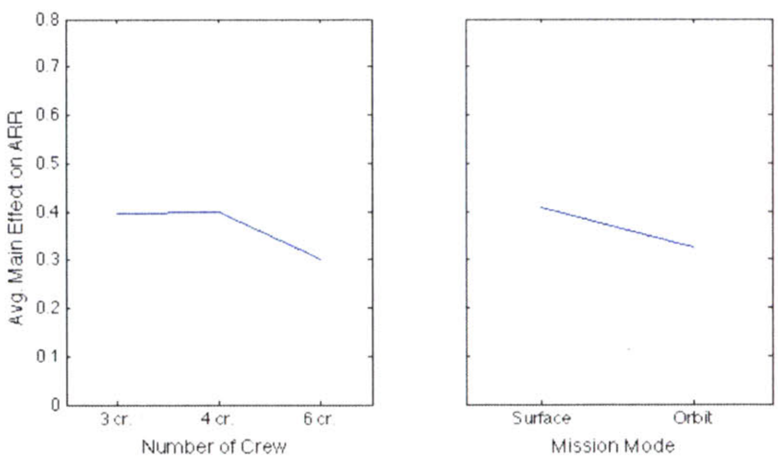



Figure 77 Ambiguity Impact Analysis – IMLEO Main Effects



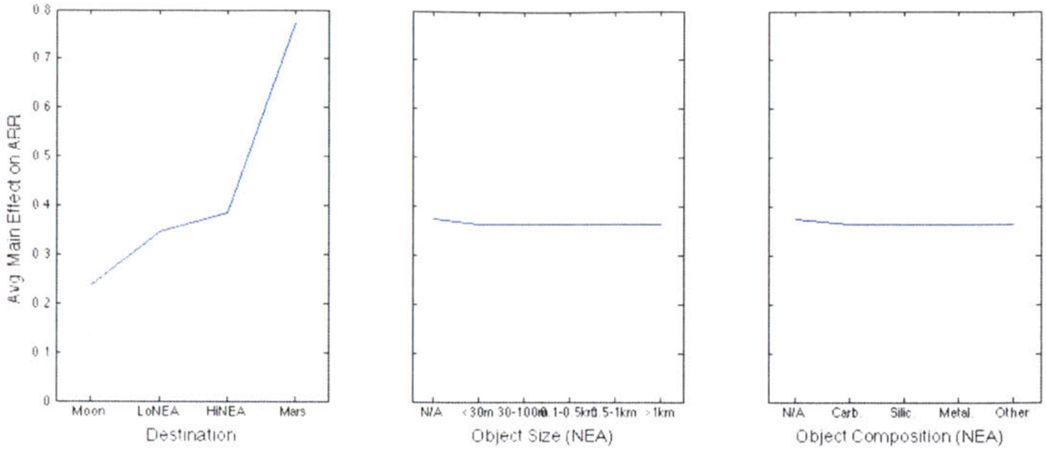



Figure 78 Ambiguity Impact Analysis - ARR Main Effects

### 5.4.8. Step 9 – Convergence Criteria

A maximum number of three iterations has been used as termination criteria for DB-SAF. The following figures (from Figure 79 to Figure 96) show the evolution of the three panels during rounds. Convergence has also be verified with experts; they confirmed that they were unlikely to change their answers in a fourth round of DB-SAF, therefore the study was called to a close.

Figure 97 to Figure 99 show a summary of convergence history for each value of the expert elicitation process of the three panels. Different lines represent different values for each property value. Iteration rounds are on the x-axis, whereas the standard deviation normalized to Round 1 is shown on the y-axis. A normalized standard deviation convergence metric has been preferred to a coefficient of variation convergence metric in this case as there were values with zero mean in some property variables. These panels, in conjunction with the analysis of results presented above and the analysis of individual expert panels allow to characterize of reducible and irreducible ambiguities encountered in the study. This leads, therefore, to the development of recommendations for this case study as discussed in the next section.

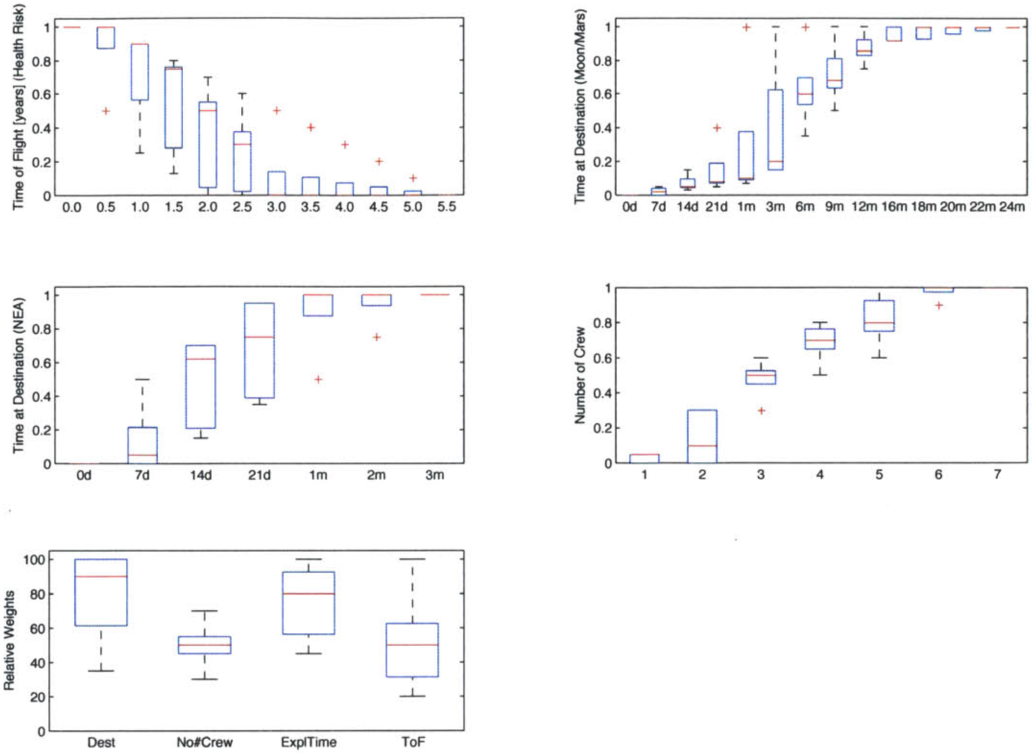



Figure 79 Exploration Panel - Round 1

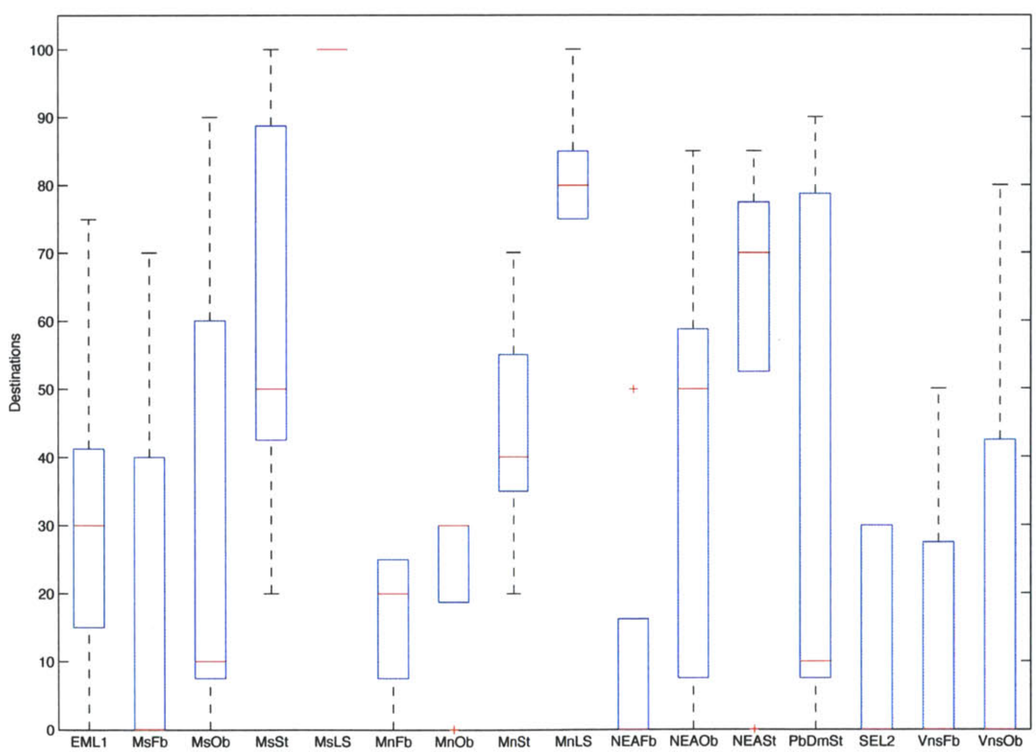



Figure 80 Exploration Panel - Destinations - Round 1

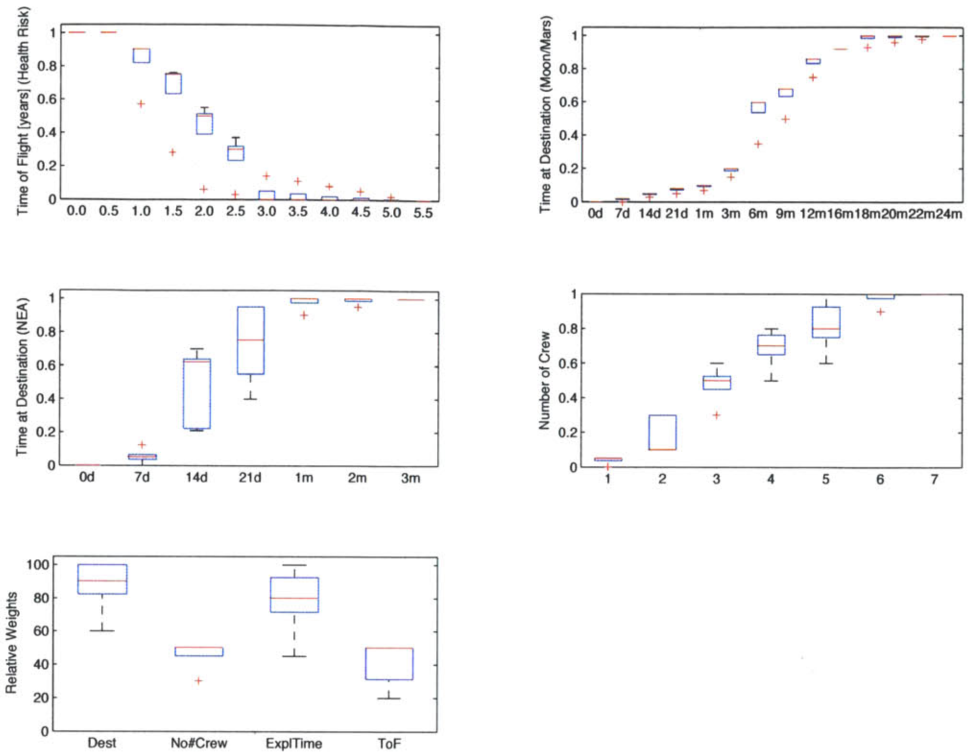



Figure 81 Exploration Panel - Round 2

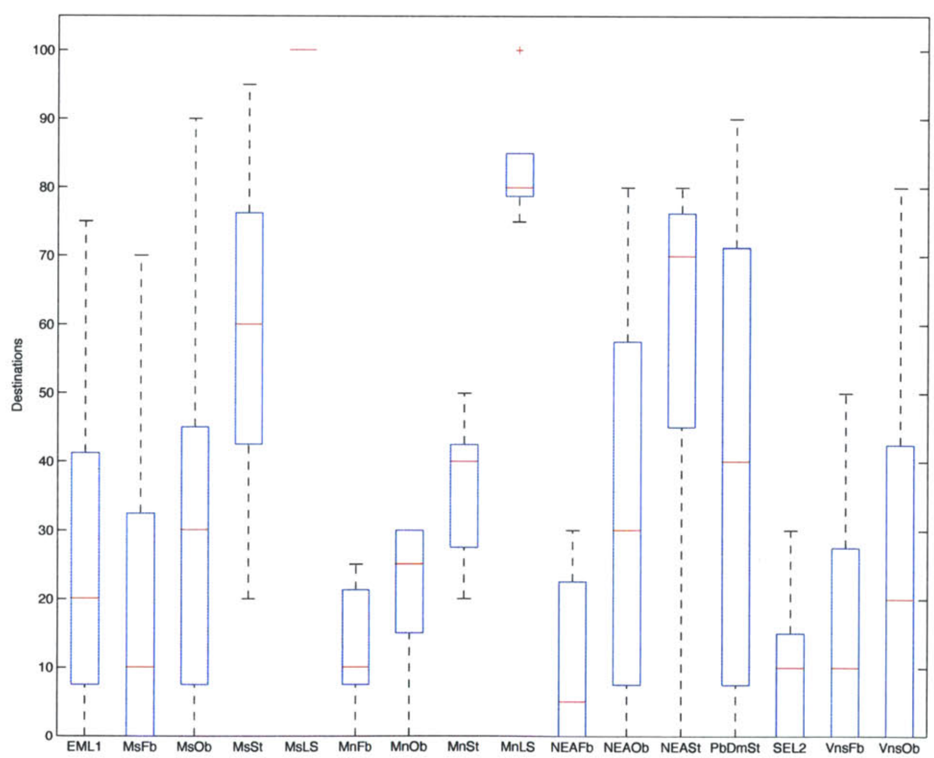



Figure 82 Exploration Panel - Destinations - Round 2

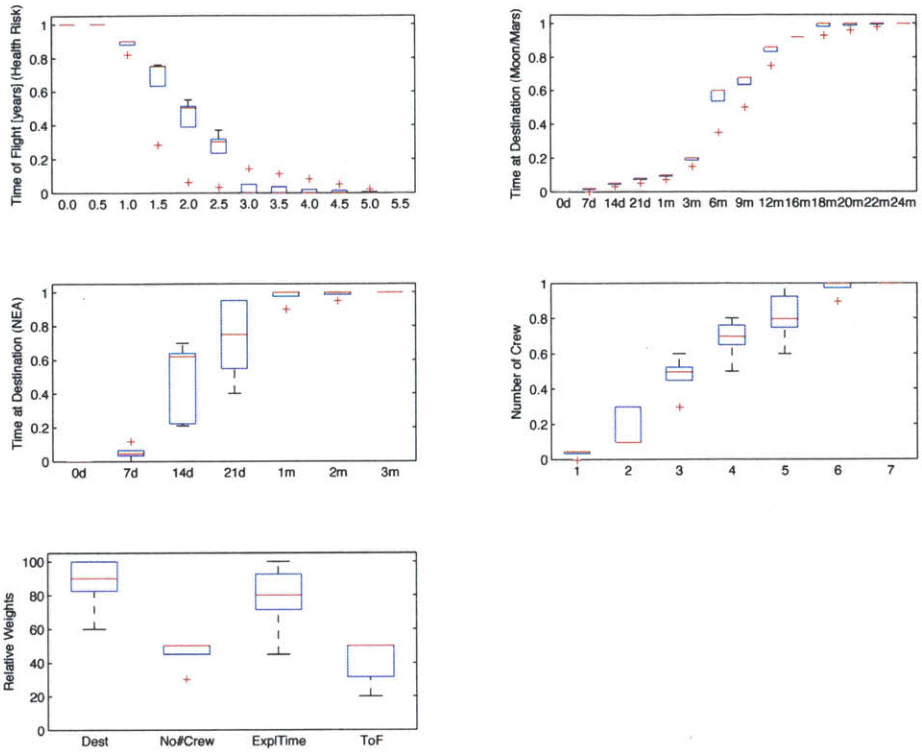



Figure 83 Exploration Panel - Round 3

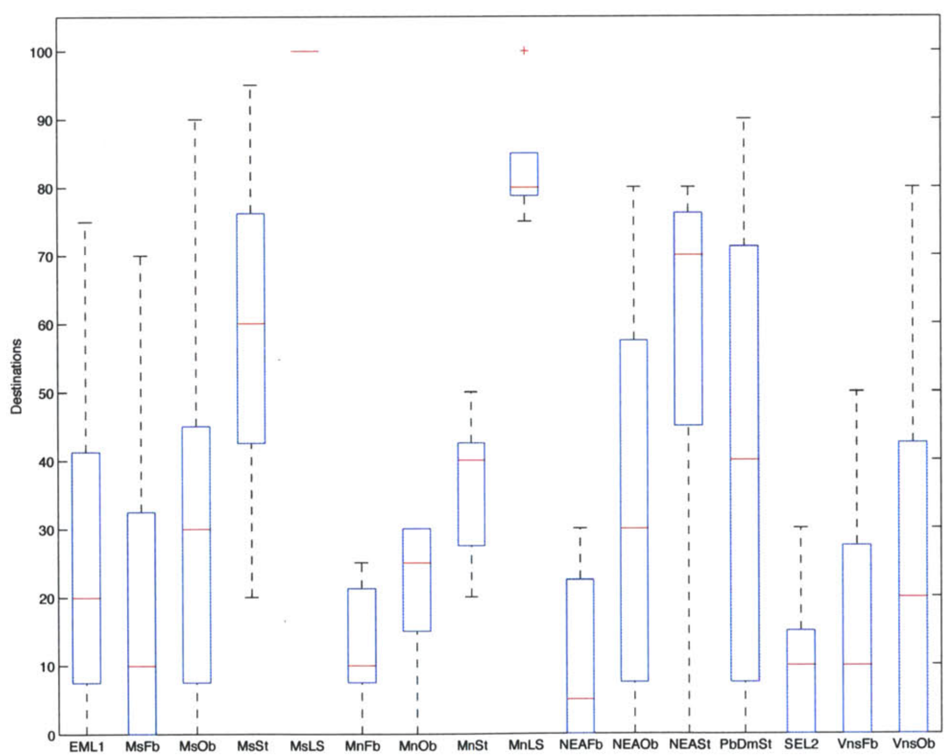



Figure 84 Exploration Panel - Destinations - Round 3

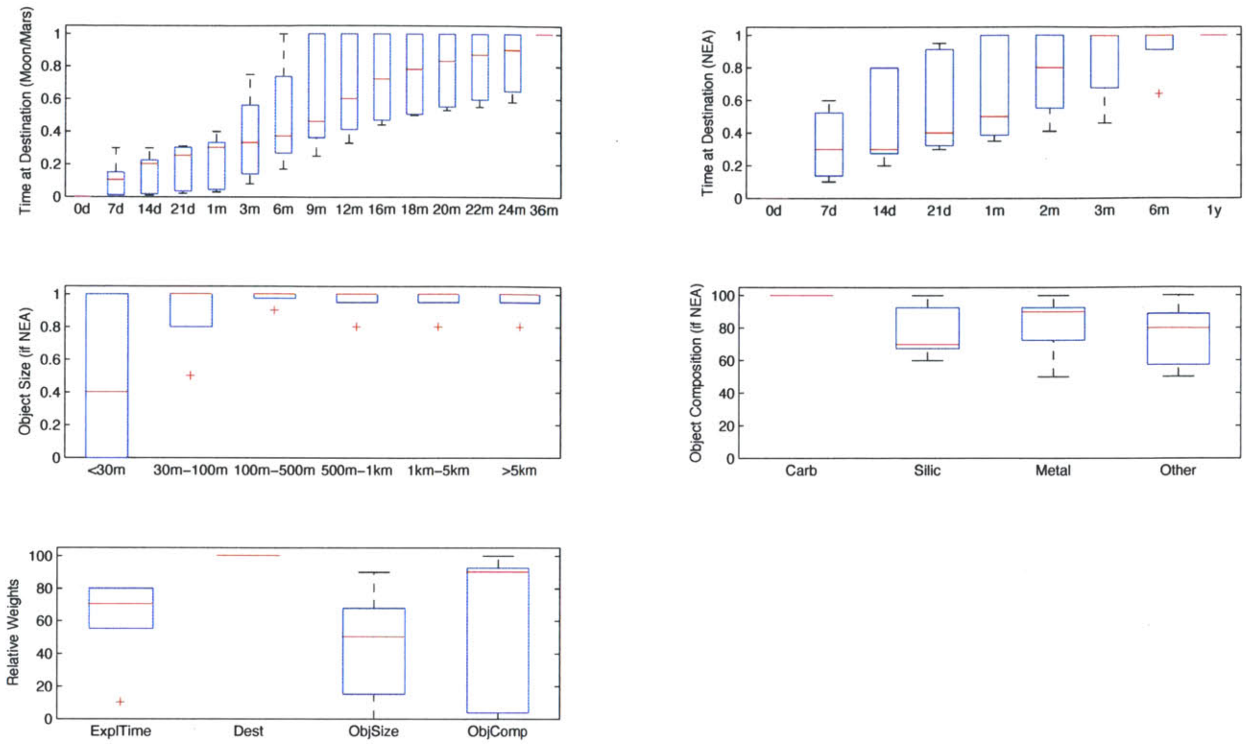



Figure 85 Science Panel - Round 1

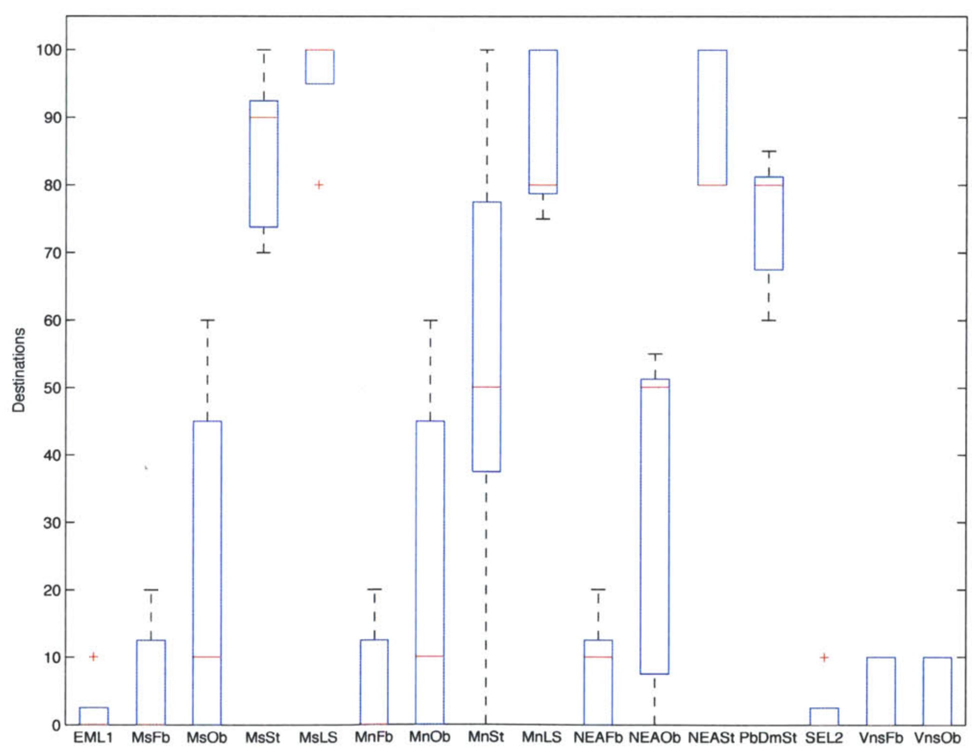



Figure 86 Science Panel - Destinations - Round 1

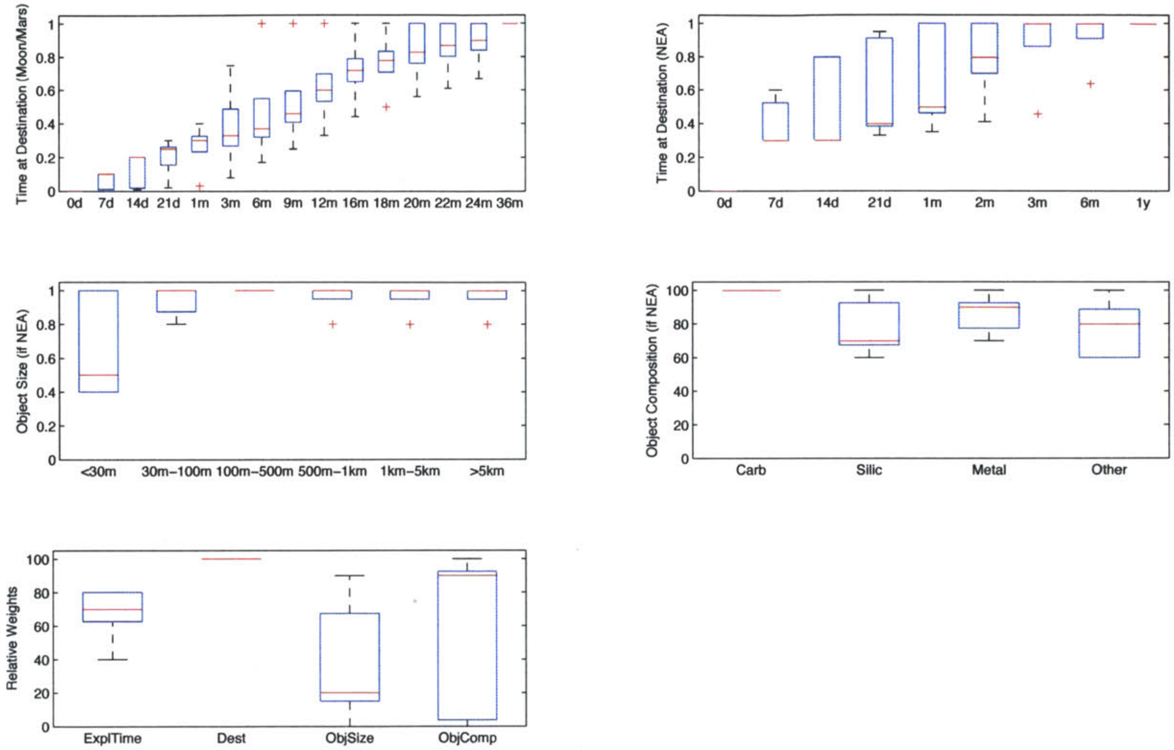



Figure 87 Science Panel - Round 2

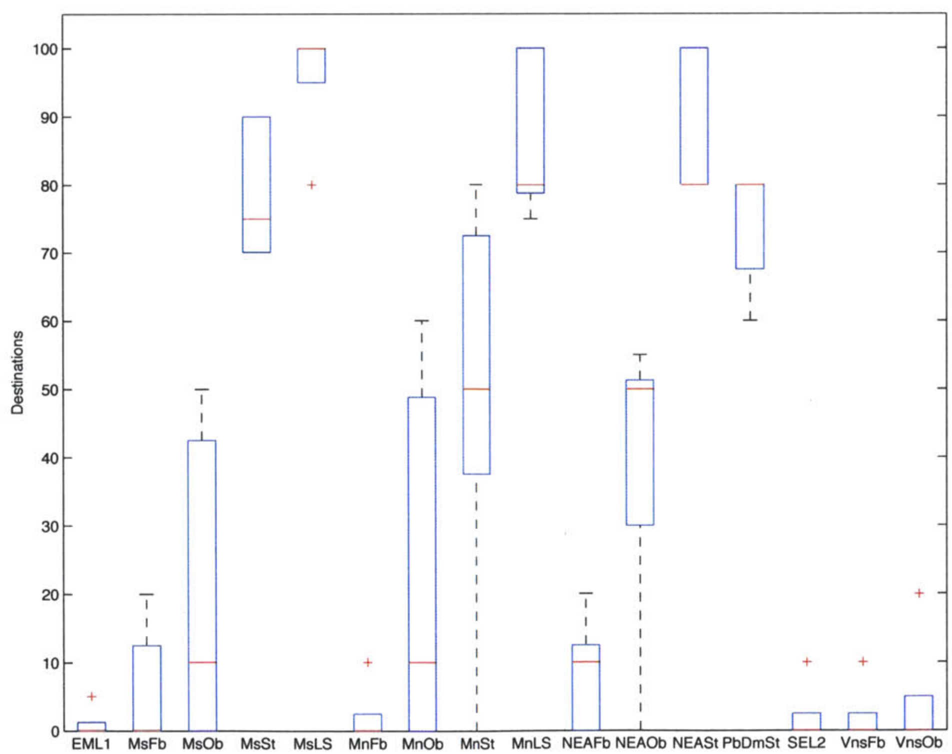



Figure 88 Science Panel - Destinations - Round 2

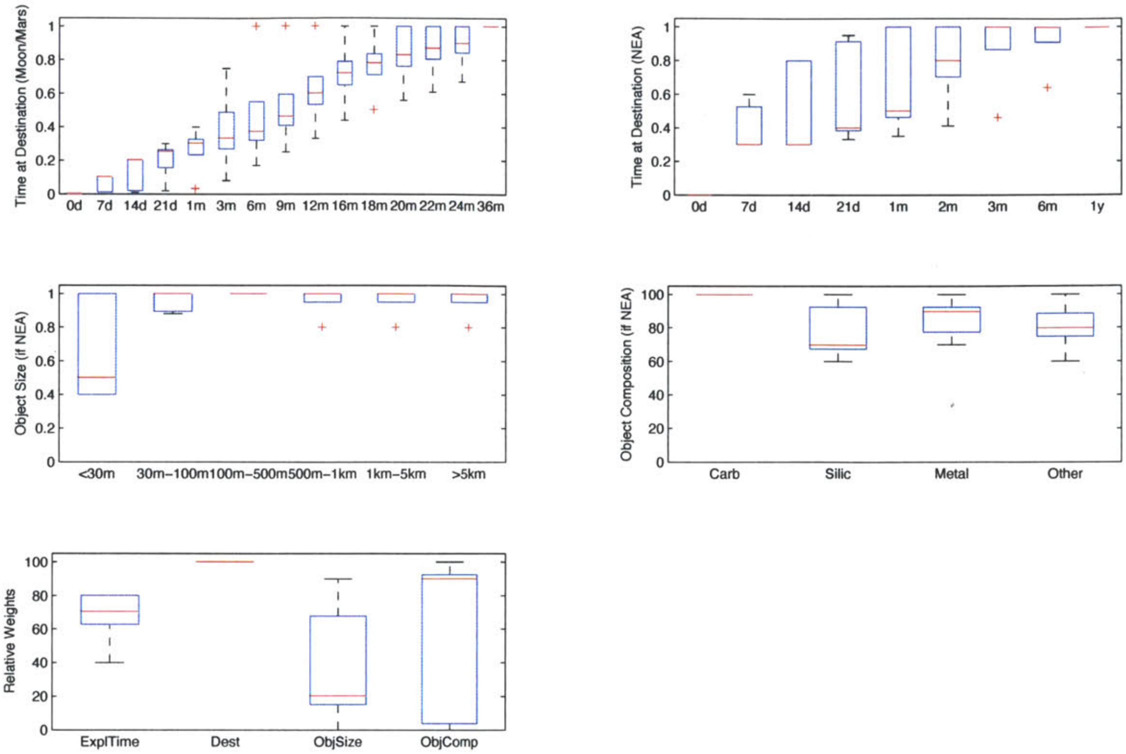



Figure 89 Science Panel - Round 3

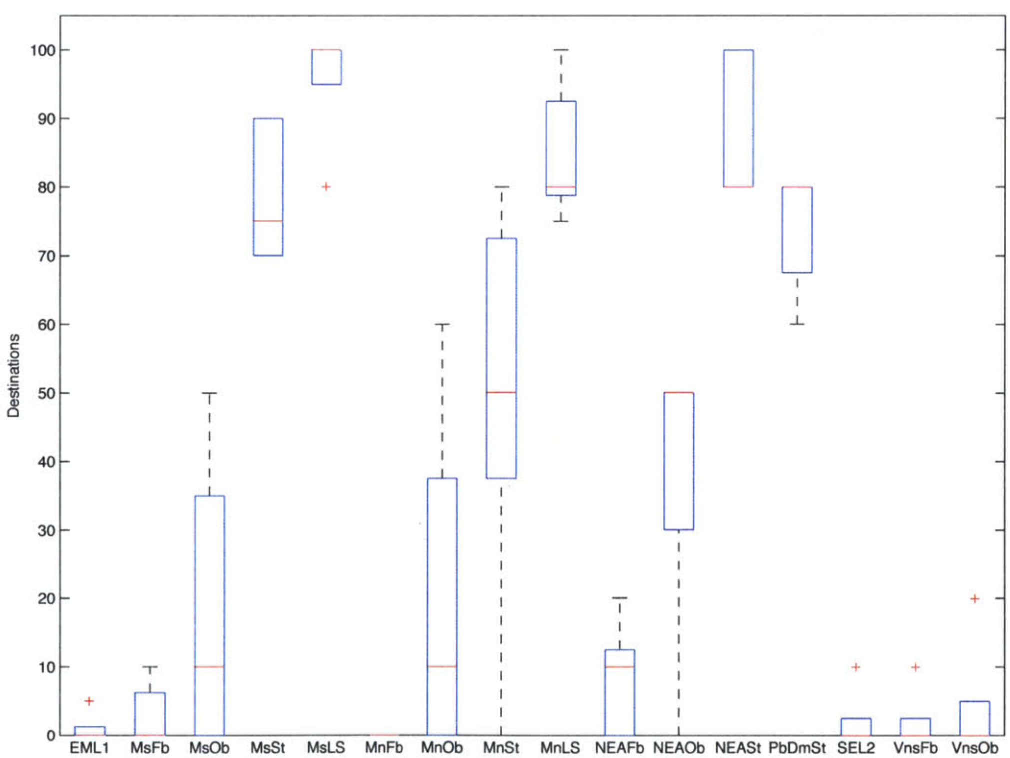



Figure 90 Science Panel - Destinations - Round 3

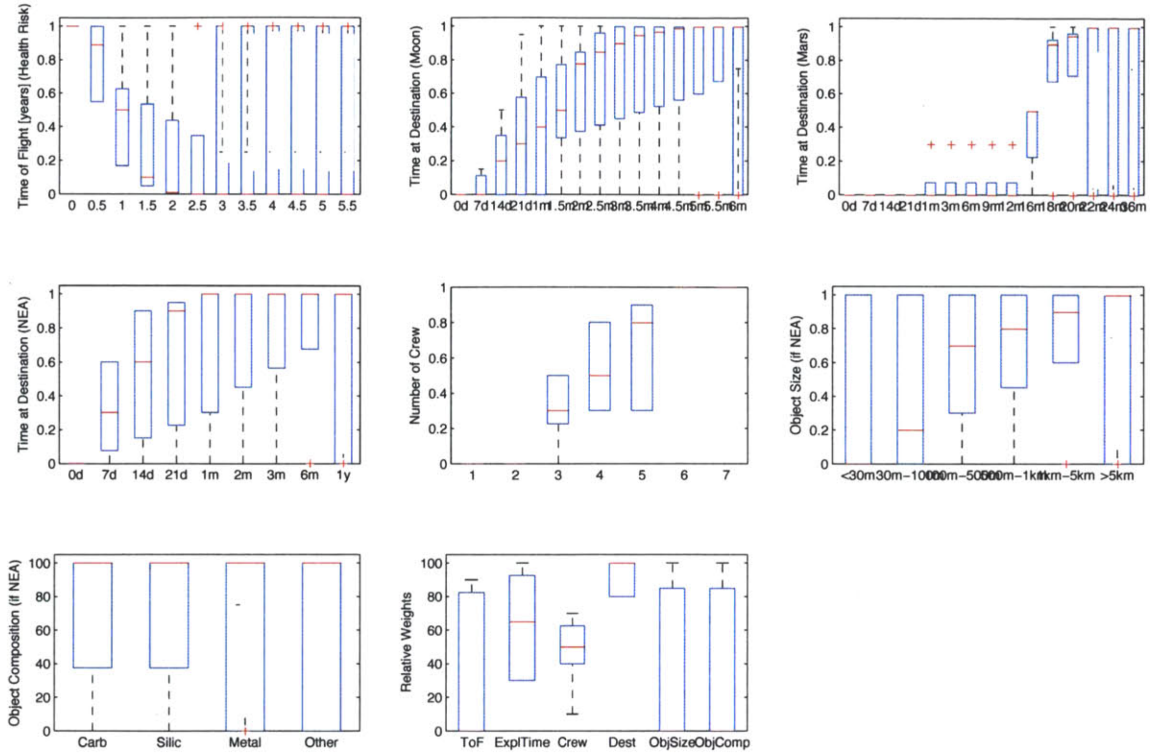



Figure 91 Policy Panel - Round 1

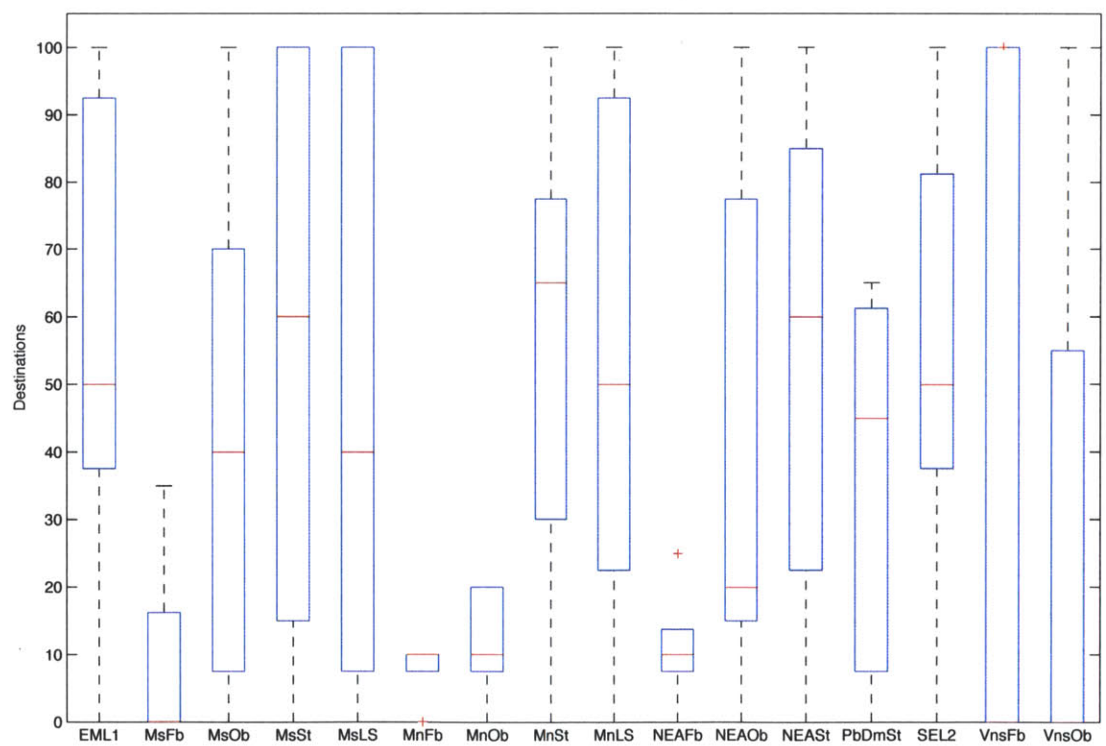



Figure 92 Policy Panel - Destinations - Round 1

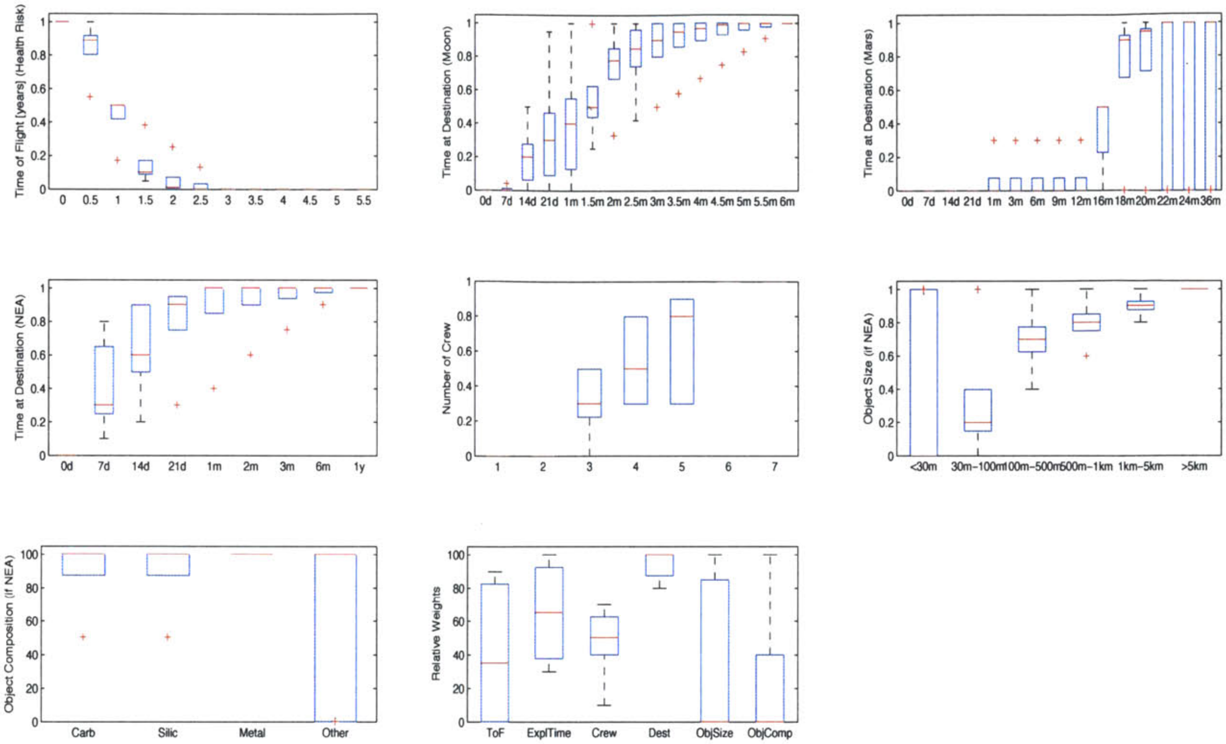


Figure 93 Policy Panel - Round 2

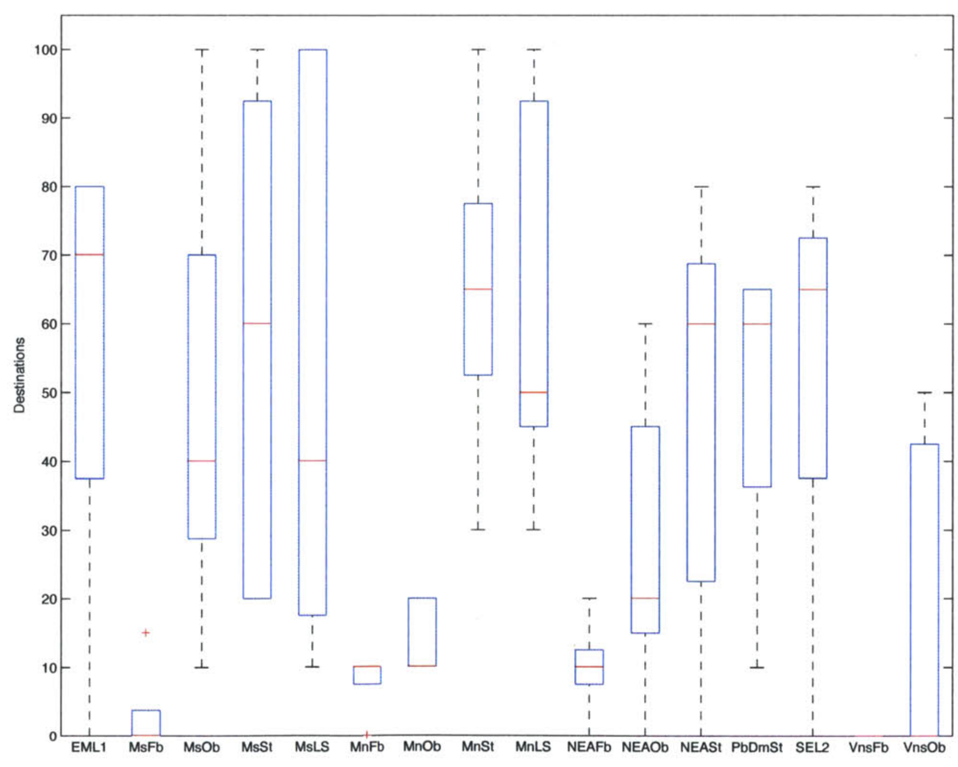


Figure 94 Policy Panel - Destinations - Round 2

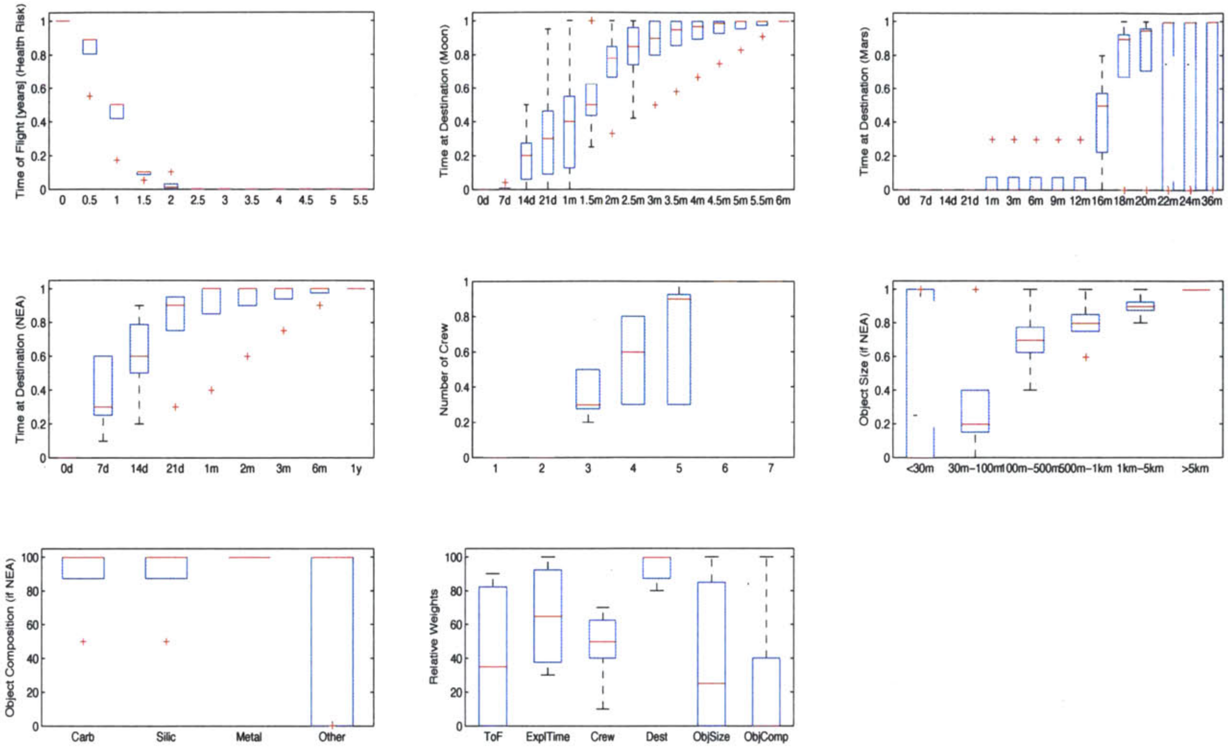


Figure 95 Policy Panel - Round 3

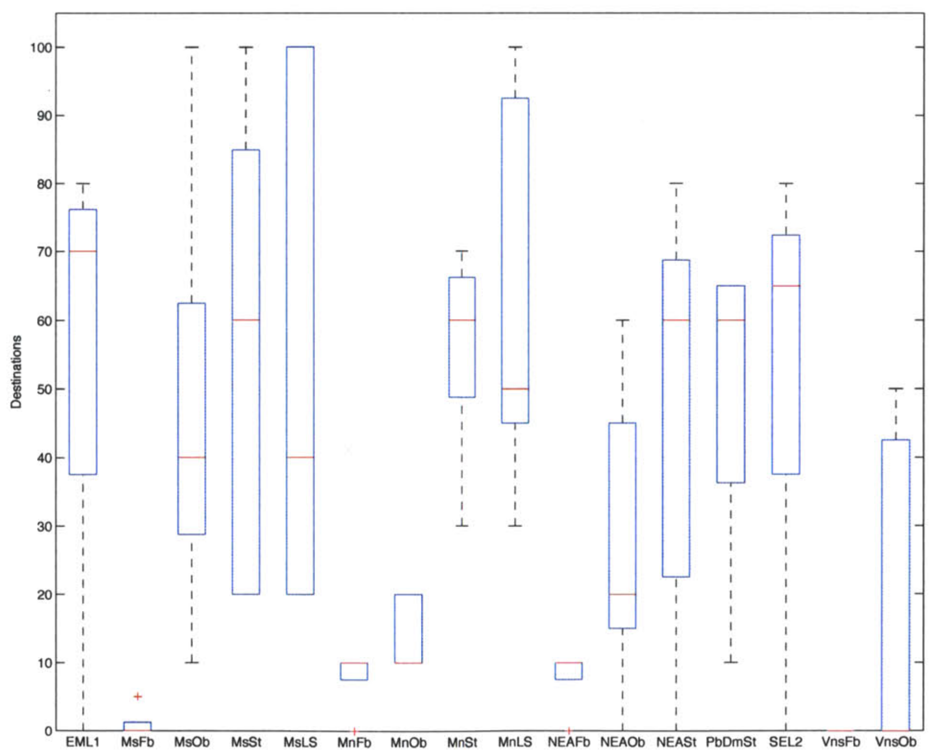



Figure 96 Policy Panel - Destinations - Round 3

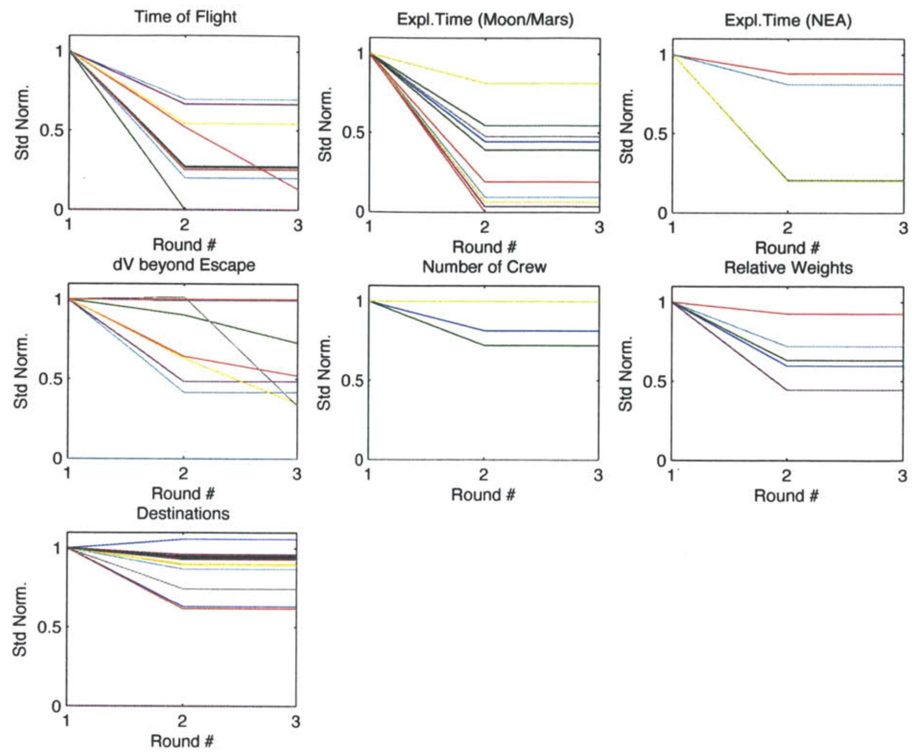



Figure 97 Exploration Panel - Convergence History

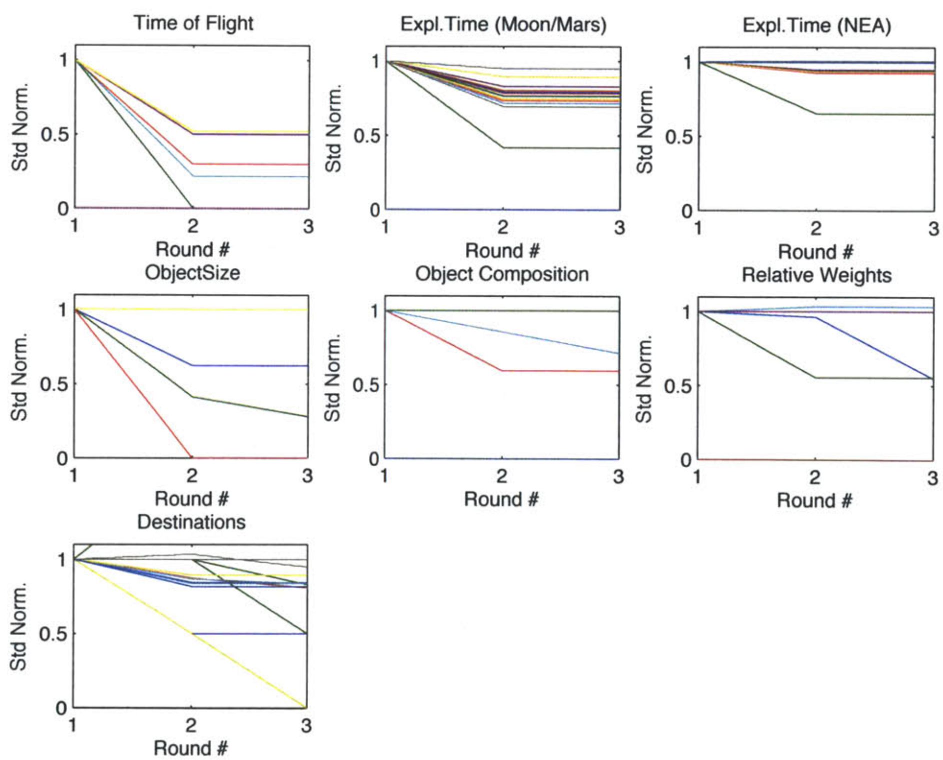



Figure 98 Science Panel - Convergence History

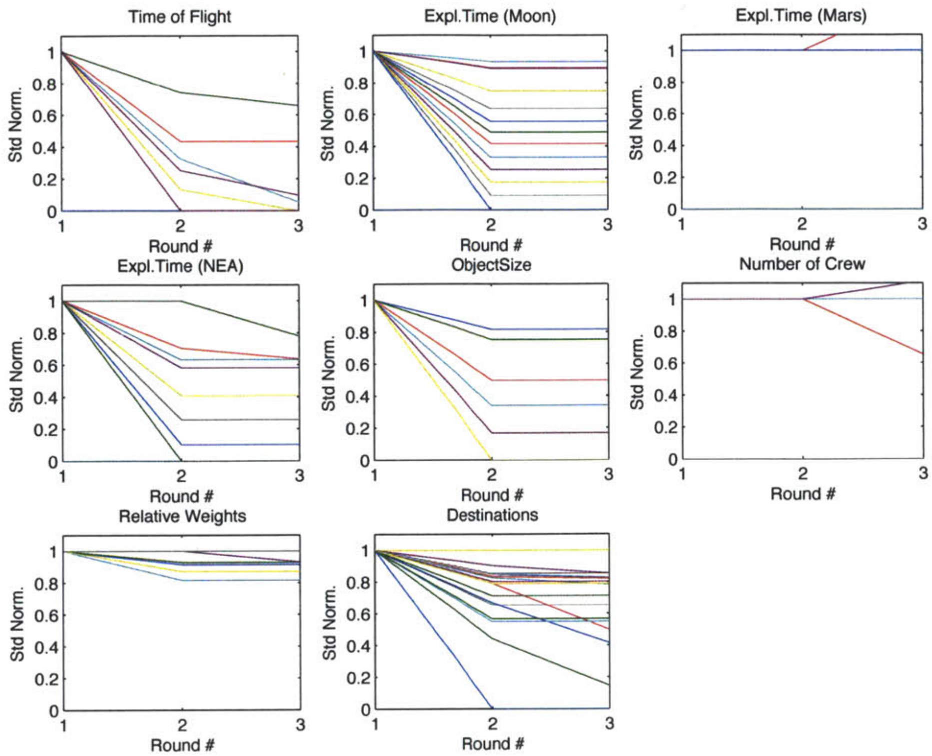



Figure 99 Policy Panel – Convergence History

### 5.4.9. Step 10 – Development of Recommendations

The following recommendations emerge from the analysis:

- The choice of a destination is the predominant irreducible ambiguity affecting the architecture of in-space transportation infrastructure, with particular impact on exploration-related and policy-related stakeholders. Reduction of this ambiguity through open debate and development of resilient human spaceflight policies is on the critical path towards a successful program for the next thirty year of human exploration (see Section 5.4.7).

- No clear leadership or consensus emerging among policy makers in setting a direction for human spaceflight, which implies the need for NASA to bring new concepts for further evaluation (see Section 5.4.6.5).

- In NEA architectures, prefer carbonaceous, large-sized (>100m) Near Earth Asteroids destinations to leverage on synergies between astrobiology and geology science questions enabled by NEA sample return retrieved with astronaut sorties (see Section 5.4.6.3).

- Develop an open standard on a detailed mission CONOPS for NEA missions to reduce ambiguity on exploration value definition (see Section 5.4.6.1).

## 5.5. Case Study Summary and Conclusions

This chapter presented a broader set of challenges than what discussed in the Mars Sample Return case study in Chapter 4. The case study presented here is focused on the systems architecture of in-space transportation infrastructure for human exploration beyond Low Earth Orbit. Sections 5.1 and 5.2 introduced the problem and provided motivations for the analysis. Section 5.3 outlined specific objectives to be achieved by the case study. Section 5.4 described the step-by-step application of the framework to the case study as per the theory outlined in Chapter 3.

A specific feature of this case study is the presence of ambiguity in the definition of the functional intent, with direct impact on value delivery to stakeholder as expressed by goals. The questions of interest considered in this case study led to the development of recommendations on the architecture of in-space transportation infrastructure. The expert elicitation process in DB-SAF identified areas of reducible and irreducible ambiguities in the exploration, science and policy panels that have been involved. Main highlights from the different panels are discussed in Section 5.4.6.2 (Exploration), Section 5.4.6.4 (Science), and Section 5.4.6.6 (Policy). A multi-performance design space exploration analysis is discussed in Section 5.4.7.

The most important result of the analysis is the identification of a critical irreducible ambiguity undermining success in delivering value for the in-space transportation infrastructure of the next three decades. The choice of a destination has a primary impact on the architecture. While NASA's program of record at the time of writing of this thesis is focused on architecting a human spaceflight mission to a Near Earth Asteroid, consensus on this architecture is far from being reached by the community at large, with particular reference to exploration and policy stakeholders. Expert evaluation of NEA missions resulted in a bimodal distribution in opinions, with experts giving high value to NEA missions at the same time of experts giving zero value to the same types of missions. This fact is of particular relevance in future mission planning, as it is a threat to stakeholder agreement in funding and supporting new systems architecting and development endeavors.

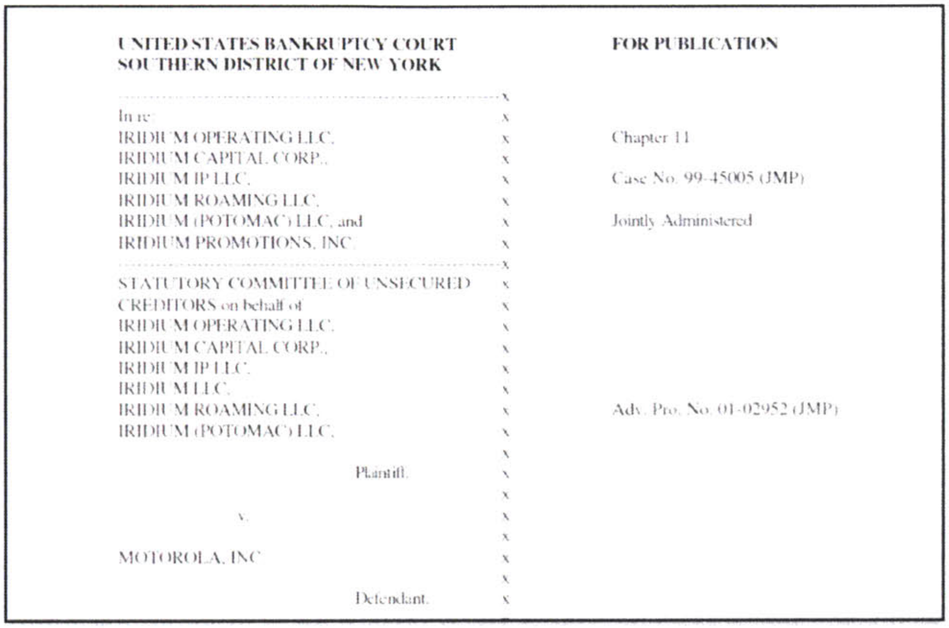
The realization of this ambiguity is a call for NASA to promote an open forum on this topic, and to develop a strong case for investments in the human spaceflight industry in the next decades by policy makers. Ambiguity and current lack of consesus in policy leadership, as emerged by this study, are critical items to be addressed in today's early design stages of the design of in-space systems for successful development, implementation, operations and value delivery of the infrastructure of tomorrow.

## 5.6. Acknowledgments

The author would like to extend his sincere gratitude to the following experts who contributed to the study: Robert Braun (Georgia Institute of Technology), Silvano Casini (former Italian Space Agency), Clark Chapman (Southwest Research Institute), Raymond Colladay (NASA Advisory Council), Simonetta Di Pippo (ESA ESTEC), Bret Drake (NASA JSC), Dave Korsmeyer (NASA ARC), John Logsdon (George Washington University), Franco Ongaro (ESA ESTEC), Ettore Perozzi (Elecnor Deimos), Andy Rivkin (JHU APL), Sara Seager (MIT), and other three contributors.

# Chapter 6 : Case Study 3 – Retrospective Validation Case Study

*"After 11 years of hard work, we are proud to announce that we are open for business. Iridium will open up the world of business, commerce, disaster relief and humanitarian assistance with our first-of-its-kind global communications service... The potential use of Iridium products is boundless. Business people who travel the globe and want to stay in touch with home and office, industries that operate in remote areas – all will find Iridium to be the answer to their communications needs."* (Iridium Satellite Communications 1998)



UNITED STATES BANKRUPTCY COURT
SOUTHERN DISTRICT OF NEW YORK

FOR PUBLICATION

In re:
IRIDIUM OPERATING LLC,
IRIDIUM CAPITAL CORP.,
IRIDIUM IP LLC,
IRIDIUM ROAMING LLC,
IRIDIUM (POTOMAC) LLC, and
IRIDIUM PROMOTIONS, INC.

Chapter 11

Case No. 99-45005 (JMP)

Jointly Administered

STATUTORY COMMITTEE OF UNSECURED
CREDITORS on behalf of
IRIDIUM OPERATING LLC,
IRIDIUM CAPITAL CORP.,
IRIDIUM IP LLC,
IRIDIUM LLC,
IRIDIUM ROAMING LLC,
IRIDIUM (POTOMAC) LLC,

Plaintiff,

v.

MOTOROLA, INC.

Defendant.

Adv. Pro. No. 01-02952 (JMP)

Figure 100 Cover page of Iridium's Chapter 11 filing (Court 1999) – "*one of the 20 largest bankruptcies in U.S. history*" (Finkelstein and Sanford 2000). Could we prevent this from happening?

## 6.1. Introduction

Chapter 4 and Chapter 5 have shown the applicability of DB-SAF to systems architecting by means of case study analysis. It has been shown how the framework can be applied to identify and characterize ambiguities in areas of consensus and compromise (*reducible ambiguities*) and areas of open debates and hidden agendas (*irreducible ambiguities*). Ambiguities are mitigated providing architectural recommendations to decision-makers. As case studies in previous chapters derive from current architecting problems – problems for which the "right" answer is unknown at present time – there is a need to strengthen the case of DB-SAF by investigating its validity and effectiveness. The analysis presented in this chapter does that by benchmarking DB-SAF results against a case for which the answer is known, or believed to be certain.

This chapter describes the validation case study that has been developed to evaluate DB-SAF and compare its performance with conventional Group Decision-Making (GDM). The remainder of the chapter is structured as follows. Section 6.2 describes the purpose of the validation and provides working definitions. Section 6.4 outlines formulating principles of the case study. Section 6.4 states the hypotheses that are being tested by means of statistical analysis. Sections 6.5 describes the case study, based on an analog that has been developed concealing a historical case. Section 6.5.2.3 outlines the protocol that has been designed for the validation, discussing criteria for population sampling and providing information on inputs, process and outputs of the validation. Section 6.7 presents a statistical analysis of results, that form the basis for drawing conclusions from the case study (Section 6.8).

## 6.2. Purpose of the Validation

The purpose of the validation is to investigate the hypothesis that the proposed *Delphi-Based Systems Architecting Framework* (DB-SAF) yields to better decision-making than what could be obtained with a *Group Decision-Making* (GDM) process. The definition of "better" is exemplified by means of validation hypotheses in Section 6.4. Stating hypotheses is effective towards validation as it provides a basis for statistical analysis.

The validation consists in an analog case study based on a historical venture that is widely regarded as a systems architecting failure. The analog case is provided as an input to an experimental study. In the study, groups of participants are called to analyze data and come with a decision regarding the development of a fictional suborbital spaceline. Biases are intentionally introduced to simulate peer pressure, ambiguity and hidden agendas in the study. Different groups are engaged in DB-SAF and GDM sessions. The effects of the biases and the effectiveness of the decision-making processes are evaluated by asking participants to compile a survey in which they are asked to evaluate the process they followed using grouped-ordinal Likert scales (Likert 1932). Survey results between DB-SAF and GDM groups are then compared using tests of statistical significance on validation hypotheses.

The case study has been inspired by the Carter Racing case (Brittain and Sitkin 1990), where a group experiment has been designed to replicate the launch/no-launch decision of the Space Shuttle Challenger. In this case, groups are proposed a concealed analog case where the management of a racing team is called to make a race/no race decision. In addition to this, the validation case study of this thesis builds on previous research that demonstrated statistical significance in decision-making quality improvements due to the availability of confirmatory and nonconfirmatory information – which is not often the case in group decision-making (Kray and Galinsky 2003). One of the strengths of DB-SAF over conventional GDM is derived by explicitly providing decision-makers both confirmatory and nonconfirmatory information during the systems architecting process, allowing identification and characterization of ambiguities.

For the purposes of this thesis the focus is on validating the requirements elicitation part of DB-SAF. The effectiveness of underlying systems architecting model for tradespace exploration has already been discussed ubiquitously in the literature by benchmark with existing systems (see (De Weck, De Neufville et al. 2004) as an example). The goal is to verify whether reduction of ambiguity, achievement of compromise, elicitation of open debate, and identification of hidden agendas occur more effectively using DB-SAF rather than a GDM expert elicitation process.

As the study employs statistical analysis as research tool, a representative and significantly large sample of participants is required. Section 6.6.2 discusses sampling criteria that have been defined to ensure representativeness of the sample. Section 6.7 discusses the optimal sample size estimate based on preliminary assumptions of target margins of error and confidence levels desired for the analysis. For the purposes of this thesis, the analysis is framed as a pilot study to estimate main effects on decision-making, inform larger scale studies and strengthen the case for DB-SAF as formulated in the cross-case analysis in Chapter 7. The following section describes the principles with which the validation case study has been designed.

## 6.3. Validation Principles

To achieve its goals, the validation is designed around the following principles:

- **Conceal** the retrospective case study with an analog case study using the same data as applied to a different context, with the intent of removing participant biases due to background knowledge on the original case study while keeping the same decision-making problem structure.
- **Simulate** the need for **team work**, due to the multidisciplinary nature of the analysis required for elicitation of stakeholder needs, formulation of a functional intent and consequent definition of system requirements.
- **Simulate** the effects of **peer pressure**, **hidden agendas** and **ambiguity** in the team work process, and their consequences in definition of system requirements hence the selection of a systems architecture.
- **Benchmark** the validity of the proposed DB-SAF against a GDM process, and therefore verify that resulting decision-making is improved as measured by success criteria described in Section 6.7.

## 6.4. Validation Hypotheses

The validation is designed to test the following hypotheses:

- **Hypothesis 1:** The average perceived effectiveness of DB-SAF in reducing adverse peer pressure effects is greater than the average effectiveness achieved by GDM among team members of a systems architecting team.
- **Hypothesis 2:** The average perceived effectiveness of DB-SAF in identifying and reducing ambiguity is greater than the average effectiveness achieved by GDM among team members of a systems architecting team.
- **Hypothesis 3:** The average perceived effectiveness of DB-SAF in improving Pareto-efficient compromises is greater than the average effectiveness achieved by GDM among team members of a systems architecting team.
- **Hypothesis 4:** The average perceived effectiveness of DB-SAF in eliciting open debate is greater than the average effectiveness achieved by GDM among team members of a systems architecting team.
- **Hypothesis 5:** The average perceived effectiveness of DB-SAF in uncovering hidden agendas is greater than the average effectiveness achieved by GDM among team members of a systems architecting team.
- **Hypothesis 6:** The average effectiveness of DB-SAF in improving decision acceptance among group members is greater than the average decision acceptance achieved by GDM.

## 6.5. Case Study Design Approach

Previous sections described the purpose, principle and hypotheses of the validation. This section describes the alternatives that have been considered in the design of the validation and the design process that has been followed for the case study.

Several avenues have been considered. All the approaches shared the idea of basing the analysis on historical cases universally recognized as architecting failures - caused by unresolved ambiguity during conceptual design. Another primary design driver that has been considered is the multidisciplinarity of the case, as represented by interconnected business, technology and policy elements in the decision-making process. The first approach being considered was that of an *a posteriori* direct approach. In this setting, a case study is discussed with a group of participants, who are called to perform an analysis "after the fact" based on input data provided by the researcher. This approach has been discarded as participants would have been biased by knowing the history of the program along with its strengths and flaws. Likewise, an *a priori* direct approach has been deemed inappropriate for validation, as the lack of a known answer does not allow objective method evaluation and benchmarking. The analysis therefore has been designed using an *a posteriori* concealed approach, where the historic case study is concealed as an analog case study. Multiple historic studies has been screened as candidates to this approach. We initially considered 1) the selection of a vehicle configuration for the Space Shuttle Program and 2) the Future Imagery Architecture cases as representatives of failures in meeting original policy objectives (Logsdon 1986; Harvey 1994; Taubman 2007). Lack of historical data in the public domain - including detailed cost, policy and technical information as available at the time of the original decision - prevented the choice of both cases. Eventually, a case based on the first commercial satellite constellations the 1980-1990s has been selected for validation. The selection has been motivated by abundant literature in the public domain in the topic, and by the multidisciplinarity of the case in its business, technology and policy facets. The choice fell over Iridium as detailed information is available in its original stock offer to the market (Communications 1999) and its Chapter 11 filing (Court 1999). The following sections presents the history of Iridium and details of the case study (Section 6.5.1) and its mapping to the analog case study that has been developed (Section 6.5.2).

### 6.5.1. Retrospective Case Study – Iridium Satellite Constellation

#### *6.5.1.1. Introduction*

Iridium is a constellation of satellites that was designed to enable space-based personal communications. Iridium was initially built and developed by Motorola, leading company in the telecommunications industry. After nurturing the project for a decade and raising capital for a total of $6 billion dollars between debt financing, shareholders and Motorola's own investment, Iridium "*solved a problem that very few customers needed solved*" (Kerzner 2009). In 1999 Iridium filed for Chapter 11 bankruptcy, becoming one of the top 20 bankruptcies in the U.S. (Finkelstein and Sanford 2000).

*"What went wrong? How did the Iridium Project transform from a leading-edge technical marvel to a multi-billion-dollar blunder? Could the potential catastrophe have been prevented?"* (Finkelstein and Sanford 2000)

#### *6.5.1.2. Brief History of Iridium*

The concept of a Mobile Satellite Service (MSS) was first proposed in 1985 by Bary Bertiger, chief engineer in Motorola's strategic electronics division (Kerzner 2009). The idea was born during a vacation in the Bahamas, when his wife Karen complained about the inability of making a phone call with her land-based mobile phone to close a real-estate transaction (Hardy 1996). Land-based cellular phone technology was emerging at the time (Bird 1985), Analysts estimated the land-based phone market to grow to 40 million customers by year 2000 (Ciesluk, Gaffney et al. 1992). Cellular technology, however, offered limited coverage due to lack of ground infrastructure. Iridium's idea was to make the "*traveller's dream come true*", by enabling personal communications on every point of the globe (Grubb 1991).

Iridium's constellation was composed of 66 satellites with a design lifetime of 5 years, relaying voice data between end user terminals and ground stations (Wilson 1998). Ground stations link to the land-based PSTN (Public Switched Telephone Network) infrastructure via dedicated gateways. Several system architectures have been proposed for MSS services by different operators (Comparetto 1993). The system architecture of Iridium is shown in Figure 101, adapted from (de Weck and Chang 2002).

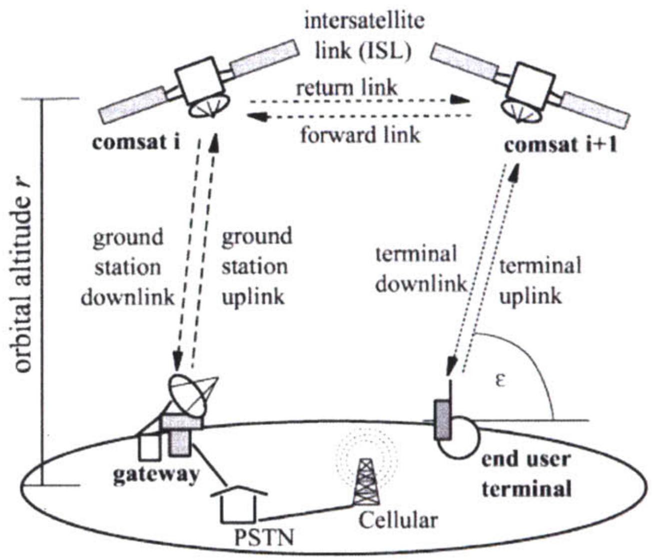



Figure 101 LEO Communication Constellation Architecture [adapted from (de Weck and Chang 2002)]

The customer target of Iridium was the global business traveler and high-end segments of the retail communications market. Significant demand for MSS services was estimated by several market surveys and analyses commissioned by Iridium (Keller 1993); in its 1990 FCC Filing, the Firm identified 15 market segments for a total of 6,076,000 subscribers by 2001 (Iridium Satellite Communications 1990) – while critics at the time argued that the service was too expensive to attract such a high number of customers (Cole 1994). Unfortunately, Iridium business plan proved to be overly optimistic, and eventually headed towards failure (Bulloch 2000; Carroll 2000). By the end of March 1998, five weeks later the introduction of Iridium to the market, the service counted 10,000 subscribers – while the company was estimating an increase of their customer base at a rate of 40,000 subscribers per month (Kerzner 2009).

A detailed history of the Iridium constellation is beyond of the scope of this thesis. (Kerzner 2009) provides a thorough account. (Finkelstein and Sanford 2000) synthesize the reasons from Iridium's collapse in the following causes:

- Unforeseen increase of capability of land-based cellular infrastructure, reducing the market interested in MSS services (Finkelstein and Sanford 2000) (De Weck, De Neufville et al. 2004);
- Iridium's *engineering limitations* (need for line-of-sight between Iridium's handheld and satellite, inability to call while in movement, inside buildings and in urban areas) (Finkelstein and Sanford 2000);
- *Schedule delays in handheld supply from manufacturers* (lacking supply of handhelds for Iridium subscribers) (Finkelstein and Sanford 2000);
- *Poor partner support* (partners delayed setup of marketing teams and distribution channels) (Finkelstein and Sanford 2000).

As uncertainty arouse on Iridium's business plan, the company kept pushing the technology through its market launch. (Finkelstein and Sanford 2000) identify three forces that created Iridium's failure:

- *Escalating commitment* – defined as "making decisions based on the size of previous investments rather than on the size of the expected return" (Finkelstein and Sanford 2000).
- *Poor Management* – the company's CEO had vested interests in pushing the technology to the market due to bonus incentives and the association of his name to the success of Iridium[6]. Furthermore, his leadership style has been described as "intimidating". In line with his company's ethic, he was a staunch supporter of Iridium, with blind faith in "his" project's success (Kerzner 2009).
- *Inadequate corporate governance* – Iridium had 27 out of 28 directors being either employees or partners' designated. Poor oversight and lack of an objective supervision led poor management practices prevail. (Kerzner 2009).

#### *6.5.1.3. Validation Question*

The Iridium project consisted of two stages: a research and development stage (1987-1996), and a manufacturing and operations stage (1996-1999) (Kerzner 2009). This study analyzes Iridium in 1996, when the corporate board made the decision of transitioning from one phase to another.

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[6] "Iridium's CEO gave up a $1.3 million per year contract with Motorola for a $500,000 base salary plus 750,000 Iridium stock options that vested over a 5-year period. Staiano [Iridium's CEO] commented: << If I can make Iridium's dream come true, I'll make a significant amount of money>> Hardy, Q. (1996). Staiano is leaving Motorola to lead Firm's Iridium Global Satellite Project. Wall Street Journal. New York." Kerzner, H. (2009). Project management : a systems approach to planning, scheduling, and controlling. Hoboken, N.J., John Wiley & Sons..

**Could ambiguities in Iridium's value proposition be identified and characterized in 1996 by supporting decision-makers with a Delphi-based systems architecting approach?**

To answer this question, an analog case study has been developed as described in Section 6.5.2. In this study, a system architecting team is called to "make or break" the case of Suborbital Spacelines LLC, a fictional aerospace venture willing to launch a point-to-point suborbital transportation service. The following section introduces this study, and shows how the case has been developed using Iridium's data in a concealed context.

### 6.5.2. Analog Case Study – Suborbital Spacelines LLC

#### *6.5.2.1. Introduction*

Suborbital Spacelines LLC is a new joint venture effort in the aerospace industry to deliver a commercial point-to-point passenger transportation service. Suborbital has conceived and designed a revolutionary concept for a spaceplane able to carry 100 passengers from London to New York in less than one hour. The spaceplane is based on a low aspect-ratio concept, powered by a hybrid rocket propulsion system, with a conventional cargo aircraft acting as mother ship at take-off. Suborbital starts where the Concorde supersonic aircraft system left, by delivering travelers new means of transportation and holding the promise of being the next breakthrough in aerospace engineering. System engineers, business analysts and policy experts at Suborbital worked together to ensure commercial viability of their concept. Fifteen initial routes have been defined for the initial plan of operations for the spaceline, covering the major business routes in the world. Additional routes have been identified for a second phase of operations, as soon as market demand unfolded in the initial stage of the service.

Suborbital plans to deliver luxury service for the high-end segment of the market, addressing customers who are willing to pay a premium to travel long distances in a reduced amount of time. Suborbital will be a first-mover in this market, as it has developed enabling technologies that are not available to competitors. Suborbital does not intend to compete with existing transportation services, rather plans to complement them with its offer.

Although competitors are not planning to develop suborbital flight services in the near term, competition threatening Suborbital's competition is at the outset. A "low cost" private jet lease service, Rent-A-Jet – inspired by the analogous service delivered by conventional low cost airlines – launched its offer to the market. While Rent-A-Jet cannot compete with Suborbital in travel time, it provides customers several perks, such as on-board Wi-Fi, custom flight schedule and the ability to operate in secondary airports closer to the customer's final destination. While Suborbital has been closely monitoring Rent-A-Jet's growth, analysts believe that its market will take a long time to grow significantly, thus not representing a threat for the Company's plans.

Following several internal systems architecting studies and commissioning external consulting companies to conduct market surveys and market sizing estimates, Suborbital managers decided to form a steering committee to analyze the Company's business case and take a final decision to authorize the transition from detailed design to manufacturing spaceplanes and operating them. The steering committee includes three panels for Business, Technology and Policy matters. Each panel is staffed by junior and senior experts, in addition to panel leads. Suborbital's Chief Executive Officer will chair the panel and will hold the final decision on Suborbital's transition to manufacturing and operations.

#### *6.5.2.2. Scope of Suborbital Spaceplanes LLD Case Study*

Scope of Surborbital's Case Study is to compare the answers and rationale provided by Team A and Team B to the following questions:

*Principal Director (CEO) Final Decision*

Should Suborbital authorize spaceplane manufacturing, infrastructure development and move to operations as per the plan proposed by the board? How will Suborbital build confidence around its decision towards shareholders?

*Business Assessment*

What business factors should the CEO consider in making its decision? What are the panel's recommendations to the CEO and why?

*Engineering Assessment*

What engineering factors should the CEO consider in making its decision? What the panel's recommendations to the CEO and why?

*Policy Risk Assessment*

What policy factors should the CEO consider in making its decision? What are the panel's recommendations to the CEO and why?

#### *6.5.2.3. Cost Model*

The cost per function (CPF) capacity-based cost model developed by (de Weck 2004) for satellite constellations has been used to model Suborbital's cost per spaceplane flight, and used in conjuction of market estimates defined in Table 34 to estimate annual revenues. Cost per function is total cost to

Suborbital per flight (expressed as \$/flights), and unit of service is the total number of expected flights per year per customer. CPF is expressed as:

Equation 1 Cost per Function model (adapted from (de Weck 2004))

$$CPF = \frac{I\left(1+\frac{k}{100}\right)^{T} + \sum_{i=1}^{T} C_{ops,i}}{\sum_{i=1}^{T} C_{s} \cdot 365 \cdot 24 \cdot 60 \cdot L_{f,i}}$$

Variables in Equation 1 are defined in Table 33, are compared between the two Iridium and Suborbital cases. Fuel cost fraction $\beta$ in Table 33 has been assumed as 1/3, similar to the fuel cost fraction of supersonic aircrafts (Davis and Eden 1967). Two flights per day were assumed in analogy with operations of the Concorde (Sobieczky 1997). Furthermore, an average spaceplane passenger load capacity of 80% - defined as the fraction of the total spacecraft capacity being used in each flight - has been assumed throughout the case study.

Table 33 Cost per Function model variables definitions

| Variable Name | Definition | Iridium Satellite Constellation | Suborbital Spacelines LLC |
|---|---|---|---|
| I | Total non-recurring investment cost | $5B | $5B |
| k | Interest rate | 3% | 3% |
| T | Design lifetime | 15 years | 15 years |
| $C_{ops,i}$ | i-th year operations cost | 300 M$/year | $C_{ops,i} = \beta\left(C_s \cdot \$_F\right)$ |
| $C_s$ | System capacity | Number of channels | $C_s = C_{sp} \cdot N_{Fl}$ |
| $L_{f,i} = \min\begin{cases} \dfrac{N_u \cdot A_u}{365 \cdot 24 \cdot 60 \cdot C_s} \\ 1.0 \end{cases}$ | Load factor | % | % |
| $N_u$ | Number of customers | Number of subscribers | Number of passengers per spaceplane = $0.8 \cdot C_{sp}$ |
| $A_u$ | Average customer activity | Number of minutes per year | Number of flights per year |
| $C_{sp}$ | Spaceplane passenger capacity | - | 100 pax |
| $N_{fl}$ | Number of flights per year | - | Flights/year |
| $\beta$ | Fuel cost fraction | - | Fuel cost % of total operating costs per flight |

## 6.6. Validation Protocol

### 6.6.1. Introduction

A *validation protocol* (Figure 102) has been developed and applied to the analog case described in Section 6.5.2. In an experiment session, two independent teams have been supplied identical data and specific questions to answer as described in the analog case scope description in Section 6.5.2.2. Team A has been instructed to approach the problem according to a GDM process, while Team B has been engaged in a structured process using DB-SAF.

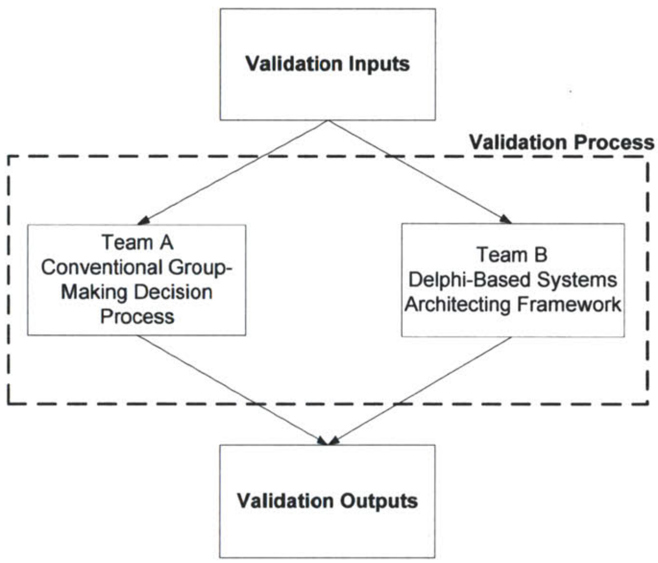


Figure 102 Study Protocol

### 6.6.2. Population Sampling Criteria

Sampling criteria have been used in allocating participants to architecting team, in order to maximize realism in results. Participants have been drawn from the MIT graduate student community. Experiments with student subject in a campus environment is a common practice in social science research. Advantages of using students as experimental subjects include the relative ease of finding participants to the study relative inexpensiveness associated with their participation. However, one could argue that students are not always the best choice for an experimental analysis. For the study to yield realistic results, it is key to ensure that participants are good representatives of the target population object of the study (Sjoberg, Anda et al. 2003). In our study the target population is composed by engineers, scientists and policy-makers that have or have had decision-making roles in their career. This population is composed of highly educated people at varying levels of experience in industry, academia, research institutions or government agencies. This target includes experts coming from different professional careers. This target is represented in the human spaceflight and Mars return case studies where panels were composed by senior experts and decision-makers. As experts were less likely to be able to participate to a validation exercise, a targeted sampling among the student population has been undertaken instead.

In order to achieve a representative sample, participants have been hired by MIT degree programs with relevant interests to this study – from Aero/Astro and the Engineering Systems Division (ESD) (representing the engineers), the Systems Development and Management Program (SDM) representing business experts with technical background, and Technology and Policy students representing policymakers. Participants have been assigned to business, engineering and policy roles according to their prior work experience. Individual teams organization is illustrated in Figure 103.

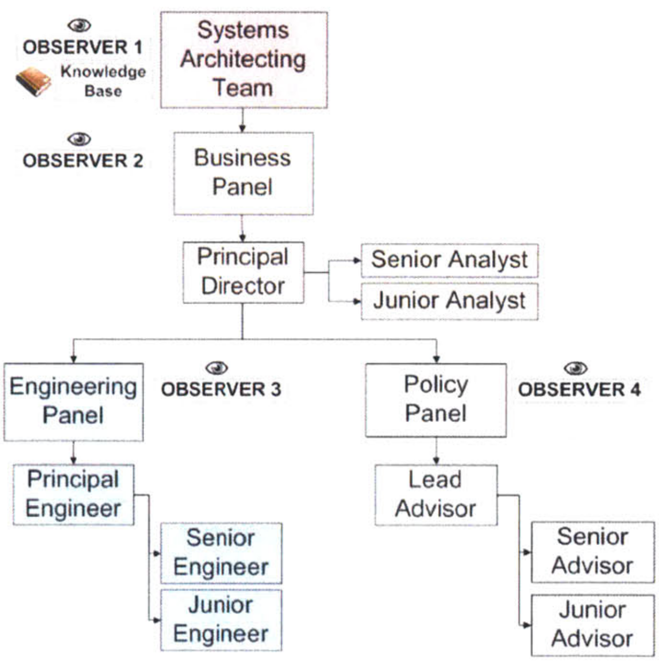


Figure 103 Team Composition

Roles were designed at different levels of the organizational hierarchy; participants were assigned the role that mostly matched their professional experience. Each expert category included one Junior Expert and one Senior Expert, led by a Principal Director, a Principal Engineer and a Lead Policy Advisor respectively. The business panel was given higher authority over the other panels, with the Principal Director having ultimate decision-making judgment, based on input provided by his advisors and the Engineering and Policy panels. The Principal Director was accomplice with the researcher, as its role was intentionally biased towards leading to adverse decision-making while assuming an authoritative leadership position. Participants were instructed of their hierarchical role and assigned a custom fact sheet as described in Section 6.6.3 (Validation Inputs). No participant in the room was supplied enough information to solve all questions asked to the group. Teamwork and sharing of information was required to come up with an informed solution. Contradicting, ambiguous information and selected biases were intentionally introduced to represent adverse conditions that affected decision-making. The goal was to check the ability of the two decision-making process in dealing with this case.

Internal validity of the experiment has been ensured by presence of non-participating observers during experimental sessions. Observers have been tasked to observe teams as non-participant peer reviewers. They recorded differences in decision-making behaviors between teams using GDM and DB-SAF. Observers have been given panel-specific instruction sheets on observables to be annotated during both team sessions that allowed consistency checks after execution of the experiments. Observers have not been allowed to share any data or participate in any discussion within the group. Observer 1 has been assigned the role of experiment supervisor, further acting as the keeper of a Knowledge Base. Experts have been allowed to either formulate assumptions behind their rationale, or to ask a single set of questions via email from the Knowledge Base to inform assumptions prior the beginning of the session. Observer 1 held approval authority on the request. Requests could have been rejected to preserve the intended design balance between positive and negative biases in the study.

#### *6.6.2.1. Sample Size Estimate*

A critical aspect in the validation is to ensure that the sample is large enough to be used to derive conclusions based on statistical analysis. Sample size is driven by the desired confidence interval (with an associated critical point value $z^*$) , target margin of error $m$ and observed variability $\sigma$ in experiments. In this study, quantitative analysis is performed on information elicited by individual participants, while qualitative observations are made on overall group dynamics as unit of analysis by aggregating information collected by observers.

Assuming that data gathered from individual participants follow a Normal distribution, the required (estimated) sample size $n$ is (Moore, McCabe et al. 2007):

Equation 2 - Sample size estimate under normality assumption

$$n = \left( \frac{z^* \sigma}{m} \right)^2$$

Section 6.7.3 discusses results of this estimate and analyzes the limitations associated with the assumption of normality for the data gathered in the context of the experiment.

### 6.6.3. Validation Inputs

A fact database to inform Suborbital's case study has been developed as set of inputs for the validation. The database has been compiled to reproduce an Iridium-analog case in the context of commercial suborbital services. Data included only information that was available at the time of the decisions in the historical case. Each fact is documented with a reference source from the literature, showing direct comparison between the two cases. Facts have been characterized as either positive or negative biases. Positive biases are those which lead decision-makers towards retrospectively good decision-making - in this case, not authorizing the transition of Suborbital/Iridium to manufacturing and operations given business/engineering/policy ambiguities. Negative biases are those which lead decision-makers towards retrospectively bad decision-making. Facts have been categorized as pertinent to business, engineering and policy and evenly spread across those categories. Table 34 at the end of this section shows the mapping of the analog case study to the retrospective case study. Individual role sheets and general information packages distributed to the GDM and DB-SAF teams are available in Appendix 9.3.

The *principles* behind the creation of the facts database are the following:

- Reproduce the decision-making process documented in the literature covering business, technical and policy history of Iridium first generation, under tailored assumptions of a concealed case study;
- Provide an even number of facts with negative and positive biases. Negative biases are biases that lead to adverse consequences in the decision-making process; positive biases are biases that lead to (retrospectively) correct decision-making.
- Provide an even number of facts for each fact category (business, technical and policy).

Fact sheets customized for each team member were developed including the following information:

- Introduction
- Study Rules
- General Assumptions of the Study
- Participant's role in the Study
- Background information
- Expert domain-relevant facts list

Principles were developed to simulate *team work need*, *peer pressure*, *hidden agendas* and *ambiguity* with the goal of testing validation hypotheses.

Fact lists reproduced *team work need across team panels* by supplying to participants a subset of facts that were relevant to their domain of expertise only (i.e. expert domain-relevant facts). According to this principle, no expert in the team would have been able to perform a holistic assessment of the system's without consulting other team members. *Team work need within team panels* has been simulated by not providing any participant the full set of his domain-relevant information. Fact sheets were designed so that their union enabled a comprehensive systems architecting analysis.

*Peer pressure* was simulated in Team A by giving influence authority to people with higher hierarchial positions, while instructing participants at lower organizational levels that hierarchy should have been respected during the GDM process. Team B was peer pressure free by virtue of anonimity of the DB-SAF process.

*Ambiguity* has been introduced "ambiguating" fact sheets, by fuzzifying numbers, randomly concealing pieces of information, and so forth. The amount of ambiguation has been calibrated as inversely proportional to the hierarchical role of the individual expert. Fact sheets were balanced such that the higher hierarchy was balanced by a higher the degree of ambiguity within facts.

*Hidden agendas* were introduced by providing specific additional instructions only to a small number of members within teams, intentionally pushing teams towards suboptimal choices that would favor individual on team-wide. The number of hidden agendas-related facts was directly proportional to the hierarchical level of each participant. This principle sets an adverse condition that biases the team towards the selection of the "wrong" answer, that determined the failure in the historical case. The investigation therefore aimed to verify whether DB-SAF could overcome this handicap by facilitating the identification of hidden agendas-related facts.

Table 34 below shows the list of facts that has been developed for the analog case study and their mapping to the retrospective case study.

Table 34 Suborbital vs Iridium Case Study Mapping

| Fact | Literature Source | Iridium Satellite Constellation | Suborbital Spacelines LLC |
|---|---|---|---|
| **Leading-edge technical feat to fulfill a need of an uncertain customer base** | (Kerzner 2009) | First time satellite constellation is conceived, developed and operated. First time no-delay "anytime, anywhere" voice communications available to market. However, as the system is the first of its kind, there is no analog example to estimate a customer base for its utilization. | First time suborbital flight service is conceived, developed and operated. First time <1hr transoceanic flights available to market. However, as the system is the first of its kind, there is no analog example to estimate a customer base for its foreseen utilization. |

| | | | |
|---|---|---|---|
| **Significant changes in technology can occur between the time customer signs up and the time the system is ready for use** | (Kerzner 2009) | Iridium spent 13 years before satellite deployment (1985-1998). | Suborbital will spend significant time in development before operations (Target: ~10 years). |
| **Perceived customer need can change over time** | (Kerzner 2009) | Market surveys sponsored by Iridium were assessed "accurate at the time of their writing" as per US court's judgment. At that time, market estimate was overly optimistic with respect to the Iridium's actual subscriber base after service launch. | Suborbital customers could prefer travelling using first-class or business-class services on conventional airlines. |
| **Development risks transitioning from engineering to manufacturing to implementation – potential undersupply of value-related operands (phones and pagers)** | (Finkelstein and Sanford 2000; De Weck, De Neufville et al. 2004; Kerzner 2009) | Software issues prevented Kyocera (Iridium's main handheld supplier) to deliver phones to customers in a timely fashion. Few phones were available in the market at launch. | Manufacturing issues might prevent Suborbital's suppliers to deliver spaceplanes and/or spaceplane spare parts within the expected schedule. |
| **Management profit opportunity associated with project success** | (Finkelstein and Sanford 2000) | "In leaving Motorola's payroll for Iridium's" (Iridium's CEO Ed Staiano) "gave up a $1.3 million per year contract with Motorola for a $500,000 base salary plus 750,000 Iridium stock options that vested over a 5-year period. Staiano commented, <<If I can make Iridium's dream come true, I'll make a significant amount of money>>" | Suborbital's CEO gave up a $1.3 million per year contract with a major airline for a $500,000 base salary plus 750,000 Suborbital stock options that vest over a 5-year period. CEO commented, <<If I can make Suborbital's dream come true, I'll make a significant amount of money>> |
| **Overly optimistic market demand estimate** | (Cole 1994; Hardy 1995; Court 1999; Bulloch 2000; Finkelstein and Sanford 2000; Lutz, Werner et al. 2000; de Weck 2004; De Weck, De Neufville et al. 2004; Kerzner 2009) | Iridium's 1991 FCC filing reports an estimated customer base of ~6 million users. In 1999, one year after launch, Iridium only had ~50,000 subscribers to its service. | Suborbital estimates a customer base of 6 million passengers per year with its worldwide operations, once their infrastructure operates at full capacity. However, forecasts might prove being inaccurate. |
| **Lack of sight in competitor's growth** | (Cole 1994; Hardy 1995; Court 1999; Bulloch 2000; Finkelstein and Sanford 2000; Lutz, Werner et al. 2000; de Weck 2004; De Weck, De Neufville et al. 2004; Kerzner 2009) | The forecast for terrestrial communication infrastructure growth was underestimating the actual high market growth of land-based wireless phone services. | Suborbital assumes its service will eat up the high-end segment of any competitors offering first-class and business-class transportation services on conventional airlines. |
| **High cost to customer** | (Court 1999; Finkelstein and Sanford 2000; de Weck 2004; De Weck, De Neufville et al. 2004; Kerzner 2009) | Phone calls through Iridium could cost up to $7/minute (1998 dollars) | Suborbital's cost per passenger is $20,000 per flight on average. Given the novelty of the service and assuming passengers will be willing to pay a premium for Suborbital's breakthrough travel |

| | | | |
|---|---|---|---|
| | | | duration, the company is planning to pose a very high profit margin on the first phase of its commercial service. |
| **Even if system never results in providing service, mother company would still have amassed valuable intellectual property that would make mother company possibly the major player for years to come in the sector.** | (Kerzner 2009) | "Over the years, Motorola achieved a reputation of being a first-mover (i.e. first to market). With the Iridium Project, Motorola was poised to capture first-mover advantage in providing global telephone service via LEO satellites." | Suborbital will be a first-mover (i.e. first to market) and will gain advantage over competitors in providing suborbital transportation for civilian applications. |
| **Multiple markets have been identified** | (Iridium Satellite Communications 1990) | Iridium identified 15 different user categories in its 1990 FCC filing. | Suborbital identified 15 different routes in its preliminary market estimate (see Annex for more information) |
| **Enable worldwide business opportunities to customers that would not be available otherwise** | (Grubb 1991; Hardy 1996) | Iridium customers are able to be in touch with the rest of the world "anywhere, anytime". | Suborbital passengers will be able to commute worldwide, enabling business opportunities that would not be available otherwise. |
| **System is complementing and not competing with existing infrastructure** | (Communications 1999) | Iridium was conceived to be used as primary service in areas where land-based phone services are not available. It is used as a backup system where land-based phone services are available. | Suborbital will not compete with the economy-class long haul transportation infrastructure, rather it would complement the first-class and business-class offer. Furthermore, Suborbital will not compete with medium-haul and short-haul passenger services. |
| **High RDT&E costs and high non-recurring costs** | (Iridium Satellite Communications 1990; de Weck 2004; De Weck, De Neufville et al. 2004; Puttalsri, Malaithong et al. 2006; Kerzner 2009) | Satellite development and launch costs totalled a $5B value in 1998 dollars. | Suborbital development and non-recurring costs will total approximately $8B in 2012 dollars. |
| **Escalating commitment phenomena** | (Finkelstein and Sanford 2000) | "The theory behind escalating commitment is based in part on the "sunk-cost fallacy"—making decisions based on the size of previous investments rather than on the size of the expected return. People tend to escalate their commitment to a project when they (1) believe that future gains are available, (2) believe they can turn a project around, (3) are publicly committed or identified with the project, and (4) can recover a large part of their investment if the | Suborbital required significant investment in its conception and development phase. Although it is true that the system is unprecedented and to be demonstrated, the business case demonstrated the opportunity for high future gains. Furthermore, Suborbital management is now identified with this ambitious project. Management must avoid project failure at all costs to avoid headlines on the media. Furthermore, in case |

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| | | project fails." | of failure, Suborbital will be able to recover a large part of the investment in terms of intellectual property and technology being developed in the project. |
| **Management reputation associated with project success** | Finkelstein, Sanford, 2000; kerzner, 995 | "Staiano (Iridium's CEO) combined his leadership style with an old Motorola ethic that argued leaders had a responsibility to support their projects. Staiano also had significant financial incentives to push the project forward, rather than cutting losses." | Suborbital CEO's reputation is anchored with the success of the company. A failure in this large scale venture would have long-term consequences on CEO's career in the future. |
| **Reliance on system developer and other third parties** | (Communications 1999) | Iridium relies extensively on third parties to perform functions critical to its operations. | Suborbital's success will rely on its suppliers and partners to deliver spaceplanes and spaceplane spare parts in a timely fashion to meet demand. |
| **Collective belief phenomena (inability or refusal to recognize failure, refusing to see the warning signs, seeing only what you want to see, fearful of exposing mistakes, viewing bad news as a personal failure, viewing failure as a damage to one's career, viewing failure as a damage to one's reputation)** | (Kerzner 2009) | "Although the literature doesn't clearly identify it, there was most likely a collective belief among the workers assigned to the Iridium Project. The collective belief is a fervent, and perhaps blind, desire to achieve that can permeate the entire team, the project sponsor, and even the most senior levels of management. The collective belief can make a rational organization act in an irrational manner." | (Positive) Suborbital is a technical marvel, developed by highly skilled engineers, a top performing management team, and a promising business case based on market estimates and surveys. /// (Negative) Suborbital might not be considering sufficiently the uncertainties around its business case, and while the engineering of the system might prove right, its business and policy case might lead to serious challenges and potential downside failures. |
| **Management desire to have their names etched in history as the pioneers of providing the new service.** | (Kerzner 2009) | "There may have also been the desire of Robert and Christopher Galvin (Motorola's chairmen at the time, ndr) to have their names etched in history as the pioneers in satellite communications." | A Suborbital success is CEO success: his name would etch in history as the pioneer in point-to-point suborbital flight. |
| **Highly leveraged capital structure (debt covenant)** | (Communications 1999; Finkelstein and Sanford 2000; Kerzner 2009) | Iridium secured multi-billion funding through equity financing with high debt leverage. However, "Iridium would be hemorrhaging cash for several more years before service would begin." and "If Iridium defaulted on | Suborbital is securing funding through equity funding with high debt leverage. However, Suborbital will not generate revenue for all its years of development. And if Suborbital defaulted, |

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| | | its debt, the investors could lay claim to Iridium's assets. But what would investors do with more than 66 satellites in space, waiting to disintegrate upon reentering the atmosphere?" | investors would be left with 100+ suborbital planes with no destination to go with. |
| **Need to obtain gateway licenses from multiple countries (licensing risks)** | (Communications 1999; Kerzner 2009) | Iridium needed to grant gateway licenses and frequency allocation agreements from more than 170 countries in the world. | Suborbital needed to grant suborbital pilot licenses and "space-way" allocation agreements from more than 170 countries in the world. |
| **Need to obtain same frequency allocation in multiple countries** | (Kerzner 2009) | Iridium needed to grant gateway licenses and frequency allocation agreements from more than 170 countries in the world. | Suborbital needed to grant suborbital pilot licenses and "space-way" allocation agreements from more than 170 countries in the world. |
| **Product does not exist yet** | (Kerzner 2009) | No satellite constellation was ever deployed and operated before Iridium. | There is no such thing as a suborbital transportation service at the time of Suborbital's development. |
| **Prototype does not exist yet** | (Kerzner 2009) | No satellite constellation was ever deployed and operated before Iridium. | There is no such thing as a suborbital prototype service at the time of Suborbital's development. |
| **System is expected to operate 24 hours a day.** | (Communications 1999) | Iridium's phone service had to be available 24/7. | Suborbital planes are expected to operate flawlessy throughout their entire operative lifetime. |
| **More capability than predecessor system** | (Grubb 1991) | More channels than GEO comsats | Much shorter travel time |
| **Enabling capabilities that were not possible before** | (Grubb 1991) | Worldwide networking | Worldwide commute |
| **First technology of its kind. "Game changer" and "technical marvel". Driving motivations of engineering team** | (Grubb 1991) | Engineers were motivated in their work as they were developing a "one of a kind" system, a milestone in history of digital telecommunications. | Suborbital is a game changer in personal transportation. It also represents a true "one of a kind" system, a milestone in the history of aerospace engineering. |
| **Reducing technical risk on multiple-use technologies** | (de Weck 2004) | Iridium's experience improved the technological readiness level with technologies associated with the satellite constellation, such as the case of inter-satellite crosslink communications. | Suborbital's experience will improve the technological readiness level with technologies associated with suborbital flight. |
| **Gain operational experience on new technologies** | | Significant technical experience has been gained in the operation of a large and complex constellation of satellites. | Significant technical experience will be gained in the operation of a large fleet of suborbital spaceplanes. |
| **Improvement of technology performance on related fields** | (Kerzner 2009) | Iridium fostered research and development efforts in improving satellite communication-related technology, such as voice and date encoding schemes, on-board avionics processing capability and so | Suborbital will foster research and development efforts in improving suborbital flight -related technology. |

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| | | forth. | |
| **Improved understanding of subsystem-related technology principles** | (Kerzner 2009) | Iridium fostered R&D efforts in communications theory for network performance improvements. | Suborbital wil foster R&D efforts in aerospace engineering for vehicle performance improvements. |
| **Limitations of system unknown yet** | (Kerzner 2009) | It was uncertain on whether Iridium would have been able to fulfill future demand. | It is uncertain whether Suborbital will be able to fulfill its entire demand in the future. |
| **System-wide testing, maintenance and repair could adversely affect system's ability to provide the service quality it anticipates.** | (Communications 1999) | Service downtime could have been generated by system-wide testing, mainteinance and repair operations. | Service downtime could be generated by vehicle-wide testing, mainteinance and repair operations. |
| **Limited system-based service capacity.** | (Communications 1999) | Need for receiver to be in sight of satellite. Cannot be used on cars or in buildings. | Need for spaceport facilities or to adapt conventional airports to new operations. |
| **System becoming a political tool during international diplomacy because of the number of jobs it creates** | (Kerzner 2009) | Need to develop ground infrastructure worldwide (gateways) to enable system operations. | Need to develop ground infrastructure worldwide (gateways) to enable system operations. |
| **System flying over multiple jurisdictions** | (Kerzner 2009) | Satellites orbit around the Earth gaining global visibility of the surface. | Suborbital spaceplanes would fly at unprecedented altitudes, requiring worldwide regulation efforts and establishment of "spaceways" |
| **Difference in policy perspective and objectives between developed and developing countries** | (Pelton and Bhasin 2000) | "There is (sic) concern among developing countries that not enough frequencies will be available to meet their future needs. | "There is (sic) concern among developing countries that not enough spaceways will be available to meet their future needs. |
| **Interoperability standards and protocols (deregulation)** | (Pelton and Bhasin 2000) | There is a standards/protocols mismatch between the bandwidth of the satellites and ground-based fiber networks. | Conventional airports cannot host suborbital flights without significant infrastructure development and operational revisions. |
| **Needed regulatory reforms to encourage adoption of new system** | (Pelton and Bhasin 2000) | "There remains <...> a concern on the part of many of the smaller third world nations that their international communications needs will get short shrift in a market-place solely driven by profits, as their markets are often too small to be profitable" | There remains a concern on the part of many of the smaller third world nations that their international transportation needs will get short shrift in a market-place solely driven by profits, as their markets are often too small to be profitable. |
| **Institutional reform of key entities** | (Pelton and Bhasin 2000) | New government entities were required to regulate the new service as it was foreseen to scale up with increasing customer demand. | New government entities or institutional reforms will be required to regulate the new service. |

| | | | |
|---|---|---|---|
| **Proper role of governmental funding** | (Pelton and Bhasin 2000) | "One school holds that satellite communications have become commercially viable and that industry should now be expected to finance the future technology needed to succeed in the 21st century. <...> The second school holds that space communications is the ony truly successful space enterprise <...> Finally, there is a third school that says commercial money can develop the commercial technology, but for key emergency and public program services <...> may make sense." | One school holds that suborbital transportation has become commercially viable and that industry should now be expected to finance this technology.There is a second school that says commercial money can develop the commercial transportation, but for key emergency and public program services government subsidize may be foreseen. |
| **Role of government in defining technical and policy objectives (centralized vs decentralized)** | (Pelton and Bhasin 2000) | There were countries (such as the US and Canada) that allowed private organizations to set technical goals for their systems. Other countries (such as Japan and the EU) saw technology as a downstream product of policymaking efforts. | There are countries that allow private organizations to set technical performance for their spaceplanes. Other countries see technology as a downstream product of their policymaking efforts. |
| **Practical stimulus to national economies** | (Pelton and Bhasin 2000) | Employment related with Iridium's ground and space infrastructure development and operations. | Employment related with Suborbital's ground infrastructure development and suborbital operations. |
| **Impressive accomplishment as nation's future objective** | (Pelton and Bhasin 2000) | First country that developed worldwide communications capabilities. | First country that developed worldwide suborbital flight commercial service. |
| **Fostering R&D of social-related applications (tele-education, tele-health, disaster monitoring, etc.)** | (Pelton and Bhasin 2000) | Additional applications could have been conceived in parallel to the main-stream voice service. | Additional applications can be conceived in parallel to suborbital passenger transportation. |
| **Government-owned competitors attempting to prevent license allocation** | (de Weck 2004) | INMARSAT tried to prevent license issue to Iridium. | Airline authorities could try to prevent flight license issue to Suborbital. |
| **Non profit competitors attempting to prevent license allocation** | (Kerzner 2009) | Astronomers tried to prevent license issue to Iridium in L-band to avoid interferences with scientific experiments (which happened indeed). | Scientists try to prevent license issue to Suborbital to avoid interferences with suborbital experiments. |
| **Export control limitations** | (Pelton and Bhasin 2000; Kerzner 2009) | Technology export, launch sharing, US government forbidding selling replacement parts to certain gateways. | Technology export, government forbidding selling replacements parts or flying spaceplanes to certain countries. |
| **Potential sanctions from local governments** | (Kerzner 2009) | Sanction risk associated with spacecraft de-orbiting. | Sanction risk associated with spacecraft failures. |

### 6.6.4. Validation Process

Participants in both GDM and DB-SAF sessions were briefed with an introductory presentation with a review of the scopes of the study and with general guidelines to follow through the simulation. The presentation is available in Appendix 9.3. The study was presented to participants as a systems architecting role play. Participants were told to participate in a 1 hour study to make a go / no go decision on transitioning Suborbital from its development to its operational phase. Every participant was given a general information package with simulation rules (available in Appendix 9.3) and specific role information with technical, business or policy decisions according to the criteria stated above. DB-SAF participants were given 3 iteration rounds to elicit information and negotiate among teams. Following the iteration rounds, the Principal Director was given the overall information and asked to make a decision. In the GDM setting, the Principal Director led a 1 hour group discussion by asking team members to perform panel-specific iterations and therefore report to the overall committee. The schedule being followed in this setting is available in Appendix 9.3. At the end of the session the Principal Director was called to make a decision. Participants were called to fill the evaluation survey that formed the basis for statistical analysis. It is important to note that the study was not meant to assess the group as the unit of analysis; rather the focus was on individual participants as units of analysis. The following section reviews the survey and describes survey design criteria that have been adopted for the study.

### 6.6.5. Validation Output

Study outputs included qualitative and quantitative data. Qualitative data has been gathered by observed, leading to observations on group dynamics. Quantitative data has been collected through individual surveys. The survey that has been used in both GDM and DB-SAF sessions is presented in Table 35. The following criteria have been followed in survey design:

- Questions were intentionally formulated as short as simple to improve participants' understanding and to allow comprehension within the limited time available for each study session.
- Redundant questions have been introduced to assess internal consistency of each participant and account for it in results analysis.
- A 4-level grouped ordinal Likert scale has been used for expert elicitation. Likert scales provided subjective scores to rate questions assessing peer pressure, ambiguity, open debate elicitation, hidden agenda uncovering and decision quality assessment as experienced by participants.
- A reduced number of levels has been used as a result of a trade-off between results resolution and overall variability. The choice allowed to calibrate the study to a reasonable sample size. This choice has been driven by a pre-pilot study that has been conducted to test and refine the questionnaire.

- Middle alternatives have been omitted from Likert scales to prevent participants choose the neutral answer in case of indecision. This choice was led following a review of analog survey debates in social science research. The "middle question" argument is an open debate in survey design (Converse and Presser 1986). The four scale approach has been deemed appropriate for the scope of this study to assess statistically significant differences between distributions of expert opinions.

Survey results is processed by means of statistical analysis. The goal of the analysis is to find statistically significant differences in expert response between GDM and DB-SAF sessions, and therefore drive conclusions on the validation. The following section overviews qualitative and quantitative survey results, describes the statistical analysis and discusses challenges and *caveats* of the validation in the generalization of its claims.

Table 35 Role play survey

**Role Play Survey**

Your Name:

Your Role:

What is your general comment on this role play?

What would you improve or change? What would you remove?

1. Rate the extent to which peer pressure influenced your answers during the case study:
   (1) very low, (2) low, (3) high, (4) very high

2. Rate the effectiveness of the meeting in reducing ambiguities on the case study:
   (1) very low, (2) low, (3) high, (4) very high

3. Rate the extent to which you think the study was driven by individual goals from certain team members:
   (1) very low, (2) low, (3) high, (4) very high

4. Rate the effectiveness of the meeting in reaching an efficient compromise within your team:
   (1) very low, (2) low, (3) high, (4) very high

5. Rate the extent to which you were able to clear the uncertainty around facts of the case study that were initially unclear:
   (1) very low, (2) low, (3) high, (4) very high

6. Rate the effectiveness of the meeting in identifying open debates (uncertain facts) of the case study:
   (1) very low, (2) low, (3) high, (4) very high

7. Rate the effectiveness of this type of meeting to let you express your true opinion without adverse influences from other team members:
   (1) very low, (2) low, (3) high, (4) very high

8. Rate the effectiveness of the meeting in identifying hidden agendas (if any) of individual team members of the case study:
   (1) very low, (2) low, (3) high, (4) very high

9. Rate the extent to which you were able to reach a satisfactory decision with other panels within the team:
   (1) very low, (2) low, (3) high, (4) very high

10. Rate the extent to which you were you able to identify decisions where further information would be required for better decision making:
    (1) very low, (2) low, (3) high, (4) very high

11. Rate the quality of the decision taken by the CEO:
    (1) very low, (2) low, (3) high, (4) very high

12. Rate the likelihood of CEO decision to turn out to be the right one in the future according to your expert opinion:
    (1) very low, (2) low, (3) high, (4) very high

## 6.7. Statistical Analysis of Results

### 6.7.1. Introduction

The study has been conducted in two phases: in the pre-pilot stage, nine participants were engaged to provide feedback to refine assumptions, information packages and test survey questions. This preparatory stage set the ground for a pilot study. The pilot has been administered to 36 participants. This format is appropriate for a first-order assessment of the main results beight sought in the validation. Section 6.8 (Summary and Conclusions) discusses lessons learnt from the pilot study and provides guidance for further generalization of the results to pursue downstream research avenues going beyond the scopes of this thesis.

### 6.7.2. Participants Statistics

Table 36 shows the overall statistics of participants who participated to the study. A strong majority of participants have been drawn from the MIT Aero/Astro Department. Graduate students from the Engineering Systems Division, the Technology Policy Program and the System Design and Management programs participated to provide policy and business rationale at different seniority levels. The split between Master's and SDM/Ph.D. candidates is approximately even.

Table 36 Participants Statistics

| **Participant Statistics** | |
|---|---|
| **Pre-Pilot Participants** | 9 |
| **Pilot Participants** | 36 |
| **Total Participants** | 45 |
| **Non-participant Observers** | 3 |
| **Program Affiliation** | |
| Aeronautics and Astronautics | 57.8% (26) |
| Engineering Systems Division | 13.3% (6) |
| Technology and Policy Program | 8.9% (4) |
| System Design and Management | 8.9% (4) |
| Other | 11.1% (5) |
| **Degrees** | |
| S.M. Candidates | 44.4% (20) |
| SDM / Ph.D. Candidates | 55.6% (25) |

### 6.7.3. Results Analysis

The first step in analyzing results is to determine a policy on how to treat inconsistencies within survey results. Study participants were given a survey of 12 questions with double redundancy – meaning that only 6 data points have been assessed from each participant. Survey consistency in social science research is typically assessed by means of Cronbach's alpha (Cronbach 1951). Cronbach's alpha is an adimensional normalized parameter that correlates variability observed across the sample set with individual expert's variability and the number of items on which internal consistency is being tested. Once a value is estimated for each expert, the alphas can be used as weights to calibrate each contribution to the overall assessment. An alternative approach consists in setting a minimum acceptance treshold. Experts falling below the treshold are not considered in the data set. Small available sample size and the reduced number of redundant questions (two) led to the choice of a worst-case analysis approach. In this approach, inconsistencies are solved by choosing the answer going against rejection of null hypotheses. A worst-case analysis is therefore robust to type I errors, i.e. false positives (Moore, McCabe et al. 2007), making it suitable for the scopes of the validation.

Figure 104 shows raw aggregate results from DB-SAF and GDM sessions. The histograms show the distribution, while the vertical dashed lines show the median values for both the DB-SAF and GDM subsets. Medians have been preferred to means being more suitable for the analysis of small samples and are more robust to the presence of outliers. A preliminary analysis shows that DB-SAF median results are greater than GDM median response in mitigating peer pressure (hypothesis 1), reducing ambiguity (hypothesis 2), achieving better compromise (hypothesis 3) and better decision acceptance (hypothesis 6). DB-SAF scored less than GDM in eliciting open debates (hypothesis 4), and achieved a tie in perceived ability of uncovering hidden agendas (hypothesis 5).

These results are in accordance with qualitative observations taken by observers during the studies on advantages and disadvantages of both methods as perceived by participants. It is important to stress that decision acceptance is not correlated to objective quality of the decision. The latter is not included in the statistics as it refers to a different unit of analysis (the group rather than the individual experts). In the study sessions that have been conducted, all GDM sessions decided for Suborbital's transition to operations. All DB-SAF sessions decided to delay the decision to gather more data on the case. While being an interesting result, further experimentation would be required to test its statistical significance. In this case, the unit of analysis is the group rather than the individual. Such result should be considered as a tendency and not as statistical significant. Still, it is an observation of interest as it proves how final consensus (as measured by acceptance of the final decision by individual experts) does not always lead to optimal results.

No decision-making support tool is able to predict the future and therefore guarantee forecasting optimality, and GDM and DB-SAF make no exception. However, tools can help improving the chances of making optimal choices by providing comprehensive analysis. These preliminary results seem to suggest that a structured tool such as DB-SAF achieves this goal more effectively than an unstructured tool such as conventional GDM.

Nevertheless, DB-SAF encountered limitations that surfaced during the study. The main drawback that has been encountered in DB-SAF is that of constraining open debate by forcing experts to share their knowledge through a structured approach with no inter-expert communication. Anonimity allows mitigation of peer pressure and availability of confirmatory and disconfirmatory results enable reduction of ambiguity and achievement of compromise. The benefits of open communication are lost in DB-SAF. However, this does not represent an issue for the case studies in this thesis, as the latter were conducted with senior experts and decision-makers with multi-year experience in the problems being assessed. Such experts had previous interactions between each other within their organization, through conferences, workshops and meetings. On the other hand, this result suggests future work for DB-SAF, where experts would be engaged in group meetings before or after elicitation sessions. The additional drawback observed in DB-SAF is that of losing the ability of assessing body language and behavioral traits in requirements negotiations. These aspects play a significant role in the identification of hidden agendas.

Notwithstanding observations on hypothesis 4 and 5, claims on other hypotheses seem to hold. Additional investigation in this chapter answers to this need of enhancing confidence in said results.

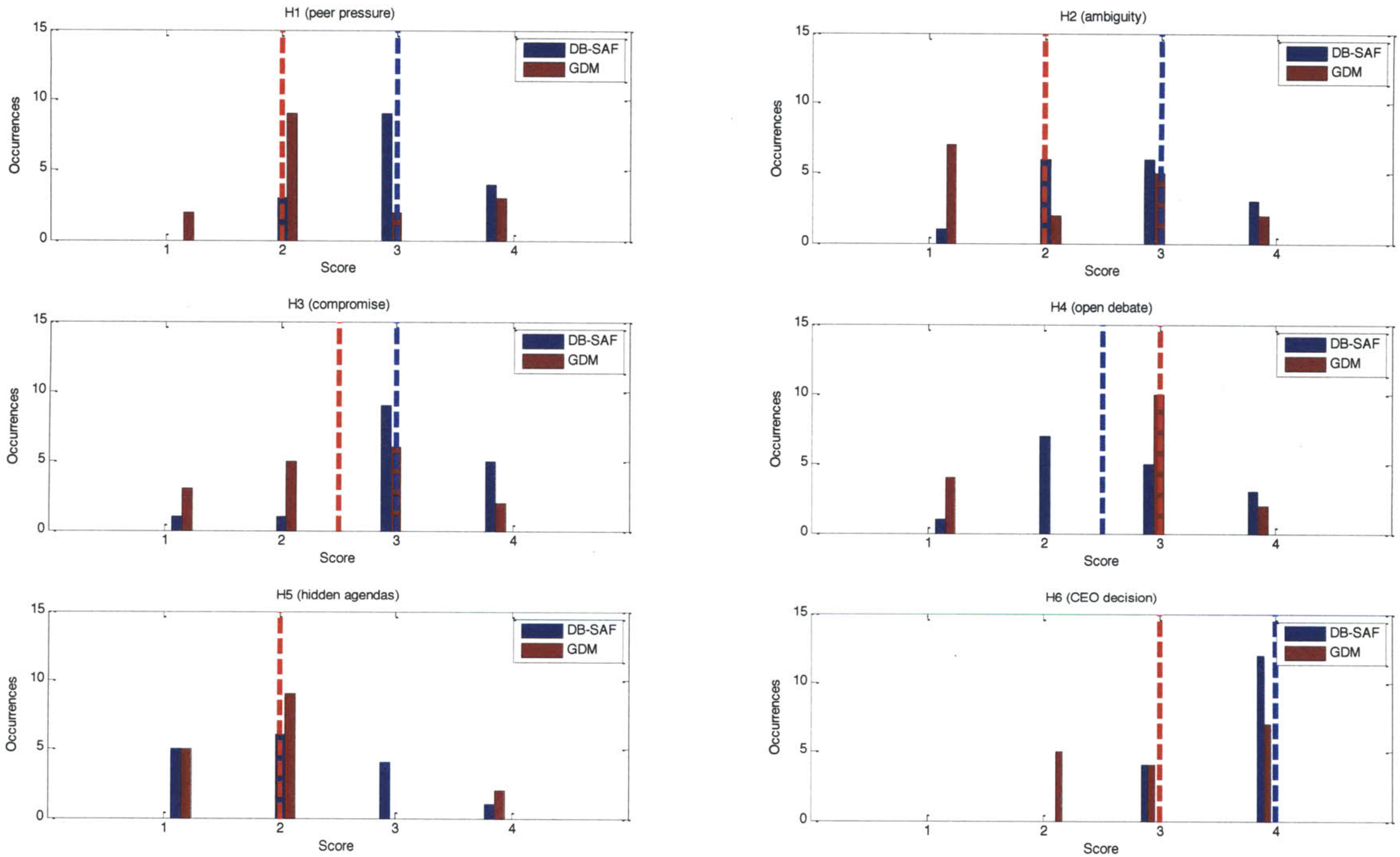


Figure 104 Survey Results - Raw Data Histograms

While the analysis of raw data provided insights on DB-SAF, a more robust approach is required to assess claims more confidently. We use statistical significance as a tool to do so. The question of interest is whether differences in median results between DB-SAF and GDM related scores are statistically significant, and if so, to what level of confidence. Two-way significance tests are conducted in this chapter.

Most tests of statistical significance rely on the assumption of data normality, such as the t-test. While t-tests are robust to small deviations from normality (which can be further mitigated by variable transformations), their use is inappropriate when dealing with small sample sets. Furthermore, the use of a 4-level scale on survey design implicitly prevents data normality even with large sample sizes. As discussed in previous sections, this choice has been motivated by the intended scopes of the validation and by the need to improve reliability of the sample set.

Two tests for statistical significance have been employed. The first one is the Wilcoxon rank sum test (Moore, McCabe et al. 2007), a non-parametric test that does not require data normality. This test is particularly suited to the application at hand is it compares ordinal ranks of the data, which has been collected in ordinal form. The Wilcoxon test is a matched-pair test that compares two populations of data (in this case, DB-SAF and GDM data) looking for statistically significant rank differences differences. The test works as follows. Two samples of data from the two populations are ranked. The Wilcoxon rank sum statistic is defined as the sum of the ranks of the first samples. This statistic is compared with the mean and standard deviation of the rank sum. The null hypothesis is rejected when the rank sum statistic is far from the mean. Table 37 shows the results of the Wilcoxon rank sum test for the six hypothesis under scrutiny. The two populations (DB-SAF and GDM data) are compared by differences in the median. The null hypothesis is rejected for hypothesis 1 (mitigate peer pressure), hypothesis 3 and hypothesis 6 at the 95% confidence level, and hypothesis 2 at the 85% confidence level. The null hypothesis cannot be rejected for hypothesis 4 (elicit open debate) and hypothesis 5 (uncover hidden agenda) at reasonable confidence levels (above 80%). Failure in rejecting the null hypothesis for hypothesis 4 and 5 is confirmation of advantages and disadvantages of DB-SAF discussed previously, and further confirmed by participants' feedback.

Table 37 Wilcoxon Rank Sum Test Results

| | P-value | Significance level | Confidence level | $z^*$ | Ranksum |
|---|---|---|---|---|---|
| Hypothesis 1 (peer pressure) | 0.0233 | 0.05 | 95% | 2.2685 | 321.50 |
| Hypothesis 2 (ambiguity) | 0.1471 | 0.15 | 85% | 1.4497 | 301.50 |
| Hypothesis 3 (compromise) | 0.0348 | 0.05 | 95% | 2.1106 | 317.00 |
| Hypothesis 4 (open debates) | 0.7631 | 0.80 | 20% | -0.3014 | 256.00 |
| Hypothesis 5 (hidden agendas) | 0.6267 | 0.65 | 35% | 0.4864 | 276.50 |
| Hypothesis 6 (CEO decision) | 0.0337 | 0.05 | 95% | 2.1233 | 314.00 |

The other approach that has been employed for statistical significance testing is the bootstrap permutation test (Moore, McCabe et al. 2007). Bootstrap methods consist in iterative resampling with replacement of the original data to approximate the distribution of mean values. These methods are particularly useful to make statistical inference on populations with skewed distributions for which the normality assumption does not hold.

In a bootstrap permutation test, the aggregate data of the original samples been tested (DB-SAF and GDM) is randomly split in two samples. In each iteration the statistic of interest is recorded; in this case, the difference of the means of the two samples. The process is iterated a sufficiently large number of times (>1,000 iterations for reference). The resulting distribution approximates the sampling of the null hypothesis. The actual statistic - the observed difference in DB-SAF and GDM means – is compared with this distribution. A significant statistic falls in the tail of the sampling distribution of the null hypothesis, as the result would rarely happen by chance. The confidence level of this statistic equals the percentile of the distribution below the statistic.

Figure 105 shows the results of the bootstrap permutation test for the hypothesis under scrutiny in this validation. Confidence levels are shown in Table 38. The results confirm the findings obtained with the preliminary inspection of results and the Wilcoxon rank sum test. Results show improved peer pressure mitigation, reduction of ambiguity, achievement of compromise and decision acceptance with DB-SAF as perceived by individual experts.

Table 38 Bootstrap Permutation Tests - Confidence Levels

**Bootstrap Permutation Tests – Confidence Levels**

*(compare with* Figure 105*)*

| *H1 - mitigate peer pressure* | *H2 - reduce ambiguity* | *H3 - achieve compromise* | *H4 - elicit open debate* | *H5 - uncover hidden agendas* | *H6 - CEO decision* |
|---|---|---|---|---|---|
| 98% | 92% | 97% | 43% | 58% | 99% |

### 6.7.4. Sample Size Check

The pre-pilot and pilot validation studies allowed to probe response variability on survey results. While interpretation of statistical data has been paired with qualitative data from observers and direct feedback from study participants, it is important to assess whether the sample size that has been employed is sufficiently large enough to have confidence in the results that have been obtained. An approximate method of doing so is assuming the data tends to follows a Normal distribution for an increasingly larger sample size – by virtue of the Central Limit Theorem. If so, we can estimate the size $n$ that is required for a sample featuring variability $\sigma$ and target margin of error $m$, with a desired confidence level represented by its associated critical value $z^*$ (Moore, McCabe et al. 2007). We assess this estimate for both DB-SAF and GDM data sets, and perform a worst-case analysis by choosing the maximum sample size estimate for a 90% confidence level and 0.44 margin of error (less than ½ point on the Likert scale). Table 39 shows the result of this analysis giving 18 as a suitable sample size. The pilot study employed a sample of 36, providing sufficient confidence in the results. Nevertheless, a larger sample size is auspicable for further generalization of these results. Section 6.8 (Summary and Conclusions) provides additional discussion of strengths and limitations of the analysis.

Table 39 Sample Size Estimate - 90% Confidence Level

| *Sample Subset* | *H1 - mitigate peer pressure* | *H2 - reduce ambiguity* | *H3 - achieve compromise* | *H4 - elicit open debate* | *H5 - uncover hidden agendas* | *H6 - CEO decision* |
|---|---|---|---|---|---|---|
| DB-SAF | 6 | 11 | 9 | 11 | 12 | 3 |
| GDM | 13 | 18 | 13 | 15 | 12 | 11 |
| Max (DB-SAF, GDM) | 13 | **18** | 13 | 15 | 12 | 11 |

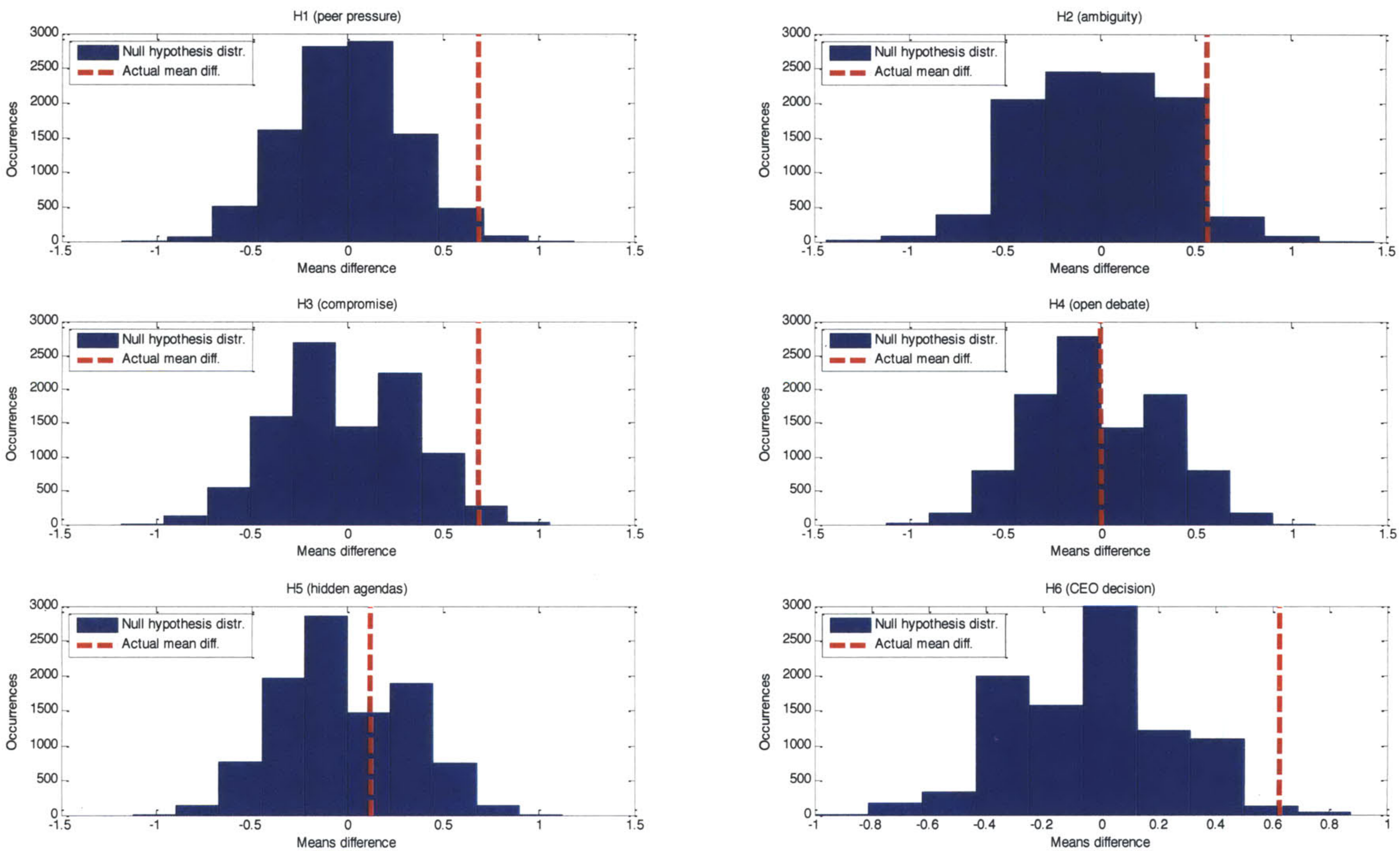


Figure 105 Survey Results - Bootstrap Shuffling (Permutation Test – 10,000 resamplings)

## 6.8. Summary and Conclusions

This chapter presented the results of a case study that has been developed to provide validation to the DB-SAF framework. Validating a decision-support tool focusing on stakeholder ambiguities is a challenge, given all the exogenous factors and behavioral phenomena that need to be considered. A concealed simulation approach has been devised to validate DB-SAF. An experimental pilot study has been designed and DB-SAF results have been compared with traditional GDM methods.

The validation uncovered strengths and limitations of the framework. DB-SAF proved being effective in mitigating peer pressure, reducing ambiguities, achieving compromises and improving decision acceptance. At the same time, the validation gave the opportunity to highlight intrinsic method challenges in eliciting open debates and uncovering hidden agendas. DB-SAF achieves beneficial results by minimizing and anonymizing inter-expert interactions. Conventional GDM, is prone to suffer from adverse effects such as peer pressure and ambiguity. On the other hand, direct expert interaction facilitates resolution of ambiguities. This tension was reflected in comparing feedback from study participants. The resulting trade-off highlights how the selection of an appropriate decision-making tool depends on the goals to be achieved by the system architects. If peer pressure, ambiguity and hidden agendas are primary concerns, then DB-SAF is probably an effective choice for decision making. If open debate and high expert interaction is preferred, GDM offers leeway to do so, at the expense of exposure to adverse effects as discussed in this chapter.

The primary challenge in this validation was to balance study breadth against fidelity. This study involved 39 participants (3 observers and 36 participants) in 2 sessions of 2 hours each. The study required complex decision-making with implications in three different disciplinary domains – business, technology and policy. Targeted population sampling criteria was used to improve the fidelity of the study.

While availability of confirmatory and disconfirmatory information facilitated identification of hidden agendas, experts participating in a DB-SAF session felt the need of direct interactions to assess intangible hidden agenda evidence such as body language, voice tone and so forth. The results of the study suggest that a hybrid of both DB-SAF and GDM methods could mitigate both these limitations, by taking the best traits from both methods while minimizing their intrinsic limitations. Further exploration of this hybrid method is an interesting avenue of future research.

Careful analysis needs to be conducted to extend the generalization of these results. One should consider the temporal dimension in decision-making. Group exercises of knowledge elicitation of any fashion are subject to change with time and participants. The same group of experts could reach opposite conclusions on a systems architecting problem if the meeting is held in different times of the year. Consider for instance the outcomes of a systems architecting team meeting of a human spaceflight mission before and after a budget decision by the White House. Likewise, different groups of experts could reach different conclusions due to unforeseen bias unbalance among the group. This limitation is minimized by have a larger group size while intentionally incorporating multiple perspectives on the problem of interest.

In addition to method-specific challenges, one must also consider limitations in the evaluation of validation-specific results. Extreme care is required to maximize the likelihood of success in reproducing subjective factors such as peer pressure, hidden agendas and ambiguity are hard to reproduce in a controlled setting. Reliability, internal consistency and external validation need to be primary concerns. Challenges include the difficulty of the target population reproducing with high fidelity – in this case, high-level decision makers and senior experts include the challenges. Participants may not be interpreting their role correctly in a behavioral simulation setting. Observers have been used to mitigate this risk.

This validation showed that one of the most challenging elements to reproduce were hidden agendas, as individuals had limited time to digest the information and to maturate a highly biased side in the discussion. Furthermore, cultural and national difference are exogenous factors that play important roles in subjective perception of leadership styles. What could be perceived as peer pressure, for instance, in a European meeting, might not in fact be perceived in equal manner in a US environment, and vice versa.

Lastly, exposing people to new problems requires simplification. Simplification is traded against realism in a case study. A validation case study must be of analog complexity to "real" case studies in order to maintain relevance to its scopes.

Notwithstanding challenges, this validation showed strong tendencies in support of major claims in the DB-SAF framework. Matching patterns observed in this controlled study with real world case studies discussed in previous chapters show evidence of improvement in systems architecting when stakeholder objectives are affected by ambiguity. Chapter 7 will expand this topic in more detail by performing a cross-case analysis and driving final conclusions of this tesis.

# Chapter 7 : Conclusions

## 7.1. Thesis Summary

Ambiguity is a threat to successful systems architecting. System architects need to identify, classify, reduce and mitigate ambiguity in early phases of the design process. Sources of ambiguity include the identification and management of stakeholders, the elicitation of stakeholder needs and needs mapping to system functions (the functional intent of the architecture). In other words, ambiguity is a threat to consider in upstream systems architecting processes together with the definition of the systems being designed (Figure 106). This thesis presented a structured framework for effective identification, classification, reduction and mitigation of multi-domain ambiguities in systems architecting.

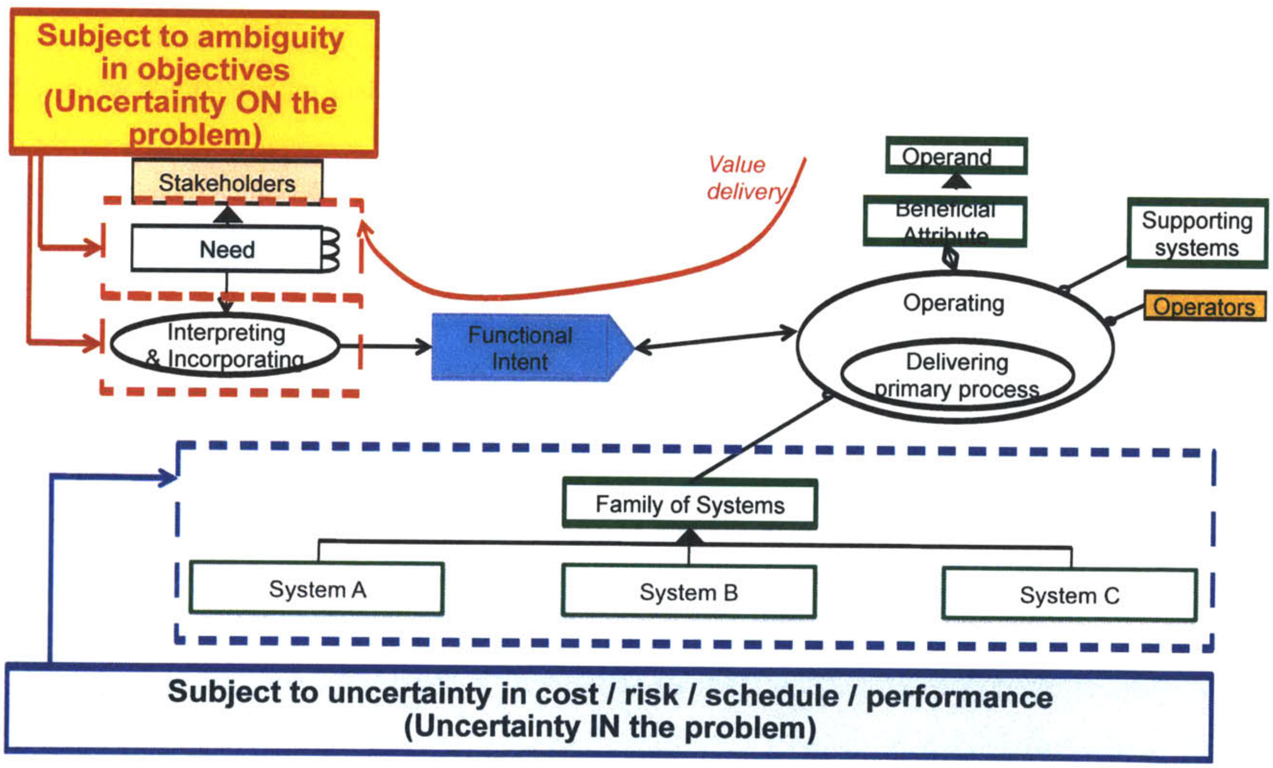


Figure 106 Distinction between processes subject to ambiguity (uncertainty ON the problem) and processes subject to risk / cost / performance uncertainty (uncertainty IN the problem)

Chapter 1 introduces the notion of systems architecting under stakeholder objectives ambiguity. The chapter describes an example from launch vehicle infrastructure systems architecting, showing how failure in considering ambiguities in requirements (such as baseline payload masses and target destinations) are threats to the value delivery process of the infrastructure in the long term, when stakeholders and needs can change in a way to invalidate the purpose of the investment. Ambiguities are important to consider early in the design process, since this is the phase when future lifecycle costs and potential for value generation are decided, and the phase of maximum leverage on system outcomes by the architect. The chapter defines the objectives of this thesis as follows:

1) **Identify** sources of ambiguity in the value delivery and tradespace exploration processes;
2) **Characterize** and model the impact of the identified sources of ambiguity on the beneficial attributes that contribute to value as delivered to stakeholders, while satisfying their needs;
3) **Mitigate** ambiguities by developing system development strategies to cut the downside effects of ambiguity while exploiting its potential upside opportunities;
4) **Integrate** the analysis of the value delivery process and functional intent definition (upstream architecting processes) with conventional tradespace exploration (downstream architecting processes). The goal is to improve the achievement of global optimaliity in the down-selection of preferred system architectures that demonstrate to be more resilient to ambiguities while still delivering value to stakeholders;
5) **Develop recommendations** to decision-makers to support final decisions concerning the selection of a system architecture for the enterprise of interest.

Ambiguity is a type of uncertainty affecting systems design. It has been defined as *nonspecificity of evidence*, *dissonance in evidence*, and *confusion in evidence* (Klir and Folger 1988). Ambiguity is a recurring theme that can be found in the engineering, design, finance, political science and social science literature. Chapter 2 presents a multidisciplinary review in this context, and identifies four research gaps in the literature, namely the recognition of ambiguity as a threat to systems architecting, the identification of different types of ambiguities (*Identify*), their classification (*Characterize*), the definition of possible mitigation strategies (*Mitigation*) and their assessment within the broader systems architecting process (*Integrate*).

Chapter 3 delves into the topic of ambiguity with an analytical approach. Starting with an ontological analysis and using set theory and first-order propositional logic, the chapter identifies four potential sources of ambiguity: 1) perceived needs of stakeholder group S, 2) perceived set of intended functions, 3) function/need mapping and form/function mapping processses, and 4) formal and functional constraints. A classification of ambiguities in systems architecting derives from the analysis. Ambiguities are classified in reducible and irreducible. Reducible ambiguities are defined as ambiguities generated by lack of understanding on known knowledge. Areas of consensus and compromise are special cases of reducible ambiguities. Irreducible ambiguities are defined as lack of understanding on unknown knowledge. Areas of open debate and hidden agendas are special cases of irreducible ambiguities. Identification and mitigation of both type of ambiguities is key information to system architects in the definition of requirements and the functional definition of a system. Given this classification, the chapter proceeds in discussing methods of expert elicitation for identification and characterization of ambiguities, distinguishing between structured/unstructured, iterative/non iterative, and anonymous/non anonymous methods. Canonical forms of ambiguity mitigation strategies are defined and described. These form a set of actions, observed in multiple fields of the scientific and engineering literature, that system architects can enact to architect their system. A descriptive Systems Architecting Management Framework (SA-MF) is defined to reconcile actions in a unified framework. A Delphi-Based Systems Architecting Framework (DB-SAF) is defined to inform mitigation actions in SA-MF. DB-SAF is a structured, iterative anonymous tool for informing ambiguity mitigation strategies as defined in SA-MF in systems architecting under stakeholder ambiguity. DB-SAF is inspired by the Delphi method in policy-making, and defines its systems architecting version in the context of formulation of new, unprecedented systems. DB-SAF consists of a structured process decomposed in the ten steps, as shown in Figure 107. The chapter describes in detail the steps of the approach and their integration with conventional systems architecting processes.

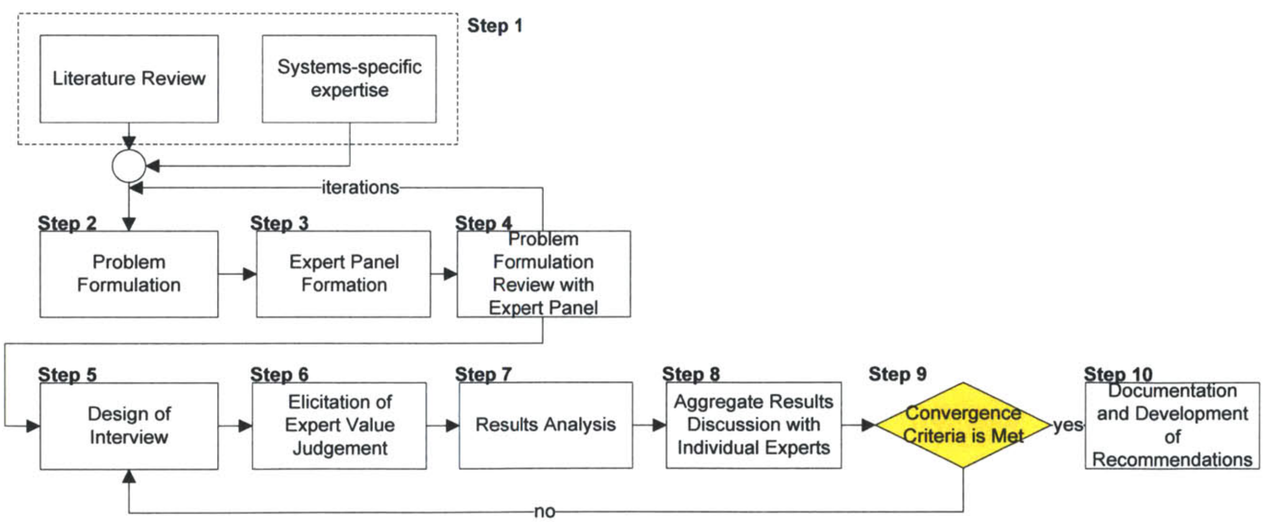


Figure 107 Proposed Systems Architecting Framework Overview

The approach presented in this thesis is applied to three application case studies. Chapter 4 presents a case study on the architecture of the Mars Sample Return Campaign, conducted at Caltech / NASA Jet Propulsion Laboratory. Chapter 5 describes a case study in systems architecting of the transportation infrastructure for human exploration missions beyond Low Earth Orbit. Both case studies are based on real architecting problems being faced by NASA at the time of writing of this thesis. Expert panels that have been involved in both case studies were all senior experts and high-level decision-makers in their respective organizations. These two case studies involved a total of 81 interviews between June 2011 and January 2012. Chapter 6 presents a validation case study that has been developed to evaluate the effectiveness of the approach as compared with existing systems architecting methods. The case study was based on a retrospective concealed validation, where a historical case study considered to have led to an architecting failure is concealed and proposed to system architecting teams, using two different architecting methods (the proposed approach, and conventional group decision-making). A survey is used to compare approach performance between cases. Surveys have been analyzed through statistical analysis. The case study highlighted advantages of the novel DB-SAF architecting approach in mitigating peer pressure, reducing ambiguities, achieving compromises and improving decision acceptance in systems architecting. Inherent limitations were surfaced such as the lack of direct interaction with experts, identifying avenues of future developments of the approach in incorporating a hybrid approach between a structured systems architecting method such as DB-SAF and conventional group decision-making processes.

The successful application of the proposed approach of systems architecting under ambiguity in stakeholder objectives for a broad array of applications, and its validation in an experimental setting, evidence the applicability of the proposed methodology to a wide category of problems in space systems architecting. While the approach has been developed with large government-funded space exploration programs, it can be extended to for-profit commercial enterprises looking to scope R&D projects with highly exploratory objectives as well.

## 7.2. Main Findings

### 7.2.1. Case-study specific Findings

- **Identification of reducible and irreducible ambiguities in the systems architecting process of the Mars Sample Return campaign.**

The Mars Sample Return case study classified ambiguities surrounding requirements definition in MSR. Property variables that have been assessed were sample types, total number of samples, sample depth, sample size and horizontal radius and their implications in engineering complexity and science value. While ambiguities on engineering complexity could be reduced to a satisfactory degree, definition of science value proved to have several areas of irreducible ambiguity. Irreducibility is due to bimodal distributions in scientific interests between astrobiology and geology objectives. Furthermore, as the Martian surface is largely unknown, several areas of open debate persist – such as on the interior composition of the planetary surface, on the definition of biomarkers that could be identified on retrieved sample types, on the definition of weathering tresholds and so forth. The case study demonstrates the impact of these irreducible ambiguities on the systems architecture of the mission. Six recommendations implementing these findings have been developed, such as to delay sub-meter drilling operations until scientists reach an agreement on the value associated with 1-meter and 10-meter drilling operations. The full set of recommendations has been discussed in Section 4.4.10.

- **Identified efficient de-scoping decisions and alternative architectures of interest for decision-makers of the Mars Sample Return campaign.**

The systems architecting analysis of Mars Sample Return identified efficient decisions that systems architect could take while in need of de-scope the mission to meet tighter cost caps. Such measures include the reduction of total number of samples retrieved on Earth, while investing at the same time in improving sample detection techniques to increase the odds of retrieving scientifically significant samples on Earth. Added capability in mobility requirements is an additional real option to invest into, in order to increase operational flexibility of the architecture and increase the size of the pool of samples at reach of the Caching rover mission. This implies investment in added instrumentation for in-situ analysis of samples composition and detection of scientific features of interest. Two-element campaign architectures are also of interest to reduce overall cost, by merging functionalities of the Fetch and Caching rovers of the current three-element campaign baseline. This approach, however, should counter-balance with the inherent increase in operational risk as the same rover would be responsible of placing sample caches to the Mars Ascent Vehicle, supposedly after a period of wait for the second-element retrieve mission to land on Mars.

- **Identification of reducible and irreducible ambiguities in the systems architecting process of the transportation infrastructure for human spaceflight missions beyond Low Earth Orbit.**

The ambiguity assessment for the human spaceflight case study (Chapter 5) identified and classified ambiguities in the definition of exploration value, science return and policy return for in-orbit infrastructure for future missions beyond LEO. Ambiguity in an exploration context could be acceptably reduced and consensus was identified among stakeholders. The only area of divergence remaining in this context is exploration value associated to 2 and 3 week stays to Near Earth Asteroids – which divergence depends on different assumptions by experts on time required for check-out and mission preparation operations in NEA missions. More irreducible ambiguity on exploration time (both on NEAs and planetary surfaces) is observed in science and policy panels. All panels agreed on health risk associated with time of flight. The dualism of reasoning of the exploration/science panels versus the policy panel is a note of interest: while the first reason through technology and scientific reasons for their judgements, the policy panel was concerned with factors such as impact on the media and policy return associated with time of flight and other property variables. Irreducible ambiguity on destinations to pursue is ubiquitous across panels, with less ambiguity observed in the science panel. As discussed in detail in Chapter 5, this result is expected due to current debate in the international arena on this topic. Several positions in this regard are identified by the study. The results of the study are useful information for concerned decision-makers in acknowledging different positions across the international community, and therefore provide support to their future decisions.

- **Identified effective architectures of interest for decision-makers of the transportation infrastructure for human spaceflight missions beyond Low Earth Orbit.**

The ambiguity analysis conducted with DB-SAF in Chapter 5 is integrated with a tradespace exploration tool to identify architectures of interest for Moon, Mars and NEA human missions. The "flexible path" concept defined in the Augustine Report (NASA 2009) is substantiated by the proposed analysis. Architectures being identified in the model are compared with mission studies available in the literature.

### 7.2.2. General contributions

- **The identification of ambiguity as a threat to upstream systems architecting processes.**

This thesis demonstrates that ambiguity is a threat to upstream systems architecting processes. The research shown in this thesis on three case studies pertaining to different fields led to the development of general insights – the canonical forms of ambiguity management, together with the SA-MF and DB-SAF frameworks - that can be used for the analysis of future problems. if ambiguity is not properly accounted in early phases of the design process, the architecture is at risk of not delivering value to stakeholders during the entire course of its lifecycle. Ambiguity must be identified, characterized and mitigated early in the lifecycle of new systems. The canonical forms of ambiguity management strategies and their encoding in the Systems Architecting Management Framework are tools enabling system architects to integrate ambiguity assessments in conventional tradespace exploration processes.

- **Ambiguity can be reducible or irreducible. Identification of both types of ambiguity is key information to decision-makers.**

Ambiguity can take different forms depending on the nature of the underlying phenomena, and whether it refers to known (knowable) or unknown information. Ambiguity is reducible when it can be eliminated and needs / judgments agreed by relevant stakeholders. Irreducible ambiguities must be properly assessed and managed to avoid adverse effects as discussed above.

- **Five canonical forms of ambiguity management strategies can be found in the literature: *Compromise, Consensus, Buy Insurance, Defer Actions, Deterrence.***

The literature review led to the identification of five fundamental strategies for ambiguity management that can be adapted for any systems architecting problem of interest. System architects can identify the appropriate management strategy by application of SA-MF and DB-SAF as described in thesis, jointly with conventional tradespace exploration tools.

- **Tailoring of expert elicitation methods for ambiguity identification and characterization is key to systems architecting.**

Expert elicitation methods are at the core of the codification of subjective value metrics in DB-SAF. Several tools are available to this end, such as ordinal scores and multi attribute utility theory. However, the choice of a particular tool must be tailored to the problem at hand. No expert elicitation tool was found to be effective for all systems architecting problem. Utility theory provides a rigorous framework for expert elicitation, however, its applicability is limited in cases where property variables cannot be translated naturally into monetary value (such as, for instance, the value associated with time of flight as a proxy for health risk to astronauts). Ordinal scores are useful to this end, however, they do not offer the same theoretical background as utility theory, and their validity depends on the effectiveness of the system architect to provide clear explanations on the meaning of individual scores. It is advisable that system architects analyze the applicability of available tools to the systems architecting problem of their interest, before delving into straightforward implementation.

- **Careful consideration of behavioral aspects is critical to successful elicitation of stakeholder needs.**

Behavioral aspects were found critical during expert elicitation sessions. As outlined in Section 3.6.7, interviews must be designed with the customer in mind, making sure to "ask the right questions", and "ask the questions right". A formally rigorous framework with no consideration of behavioral aspects that emerge in interviews are destined not to meet their original goals. Tradeoffs in rigor, expert time availability and wording must be carefully assessed before execution of interviews in the field. As expert time is a valuable resource, it is imperative not to miss the opportunity of retrieving valuable data for mistakes in the elicitation process that could have been detected beforehand by prior analysis. Testing interviews with "pilot interviewees" is an effective method to mitigate this risk.

- **Integrated exploration of feasible requirements sets and associated systems allow the identification of architecture that are robust to changes in stakeholder needs.**

The ambiguity analysis framework is integrated to conventional tradespace exploration tools to produce meaningful insights from a systems architecture perspective. The impact of selected ambiguities on system architecture metrics of interest is key to prioritize efforts in ambiguity mitigation.

## 7.3. Summary of Thesis Contributions

This thesis identified and fulfilled four gaps in the literature as identified in the literature review presented in Chapter 2. The dissertation proposed four methodological contributions:

- The use of ontological analysis as a tool for analysis of engineering systems for the identification of sources of potential ambiguity in upstream systems architecting processes.
- A taxonomy for classification of ambiguities in reducible and irreducible ambiguities, discussing their relevance to systems architecting.
- The formulation of canonical forms of ambiguity mitigation strategies in the systems architecting context, and the development of a descriptive Systems Architecting Management Framework (SA-MF).

- The integration of ambiguity identification, classification and mitigation in broader systems architecting processes, as demonstrated by the development of the Delphi-Based Systems Architecting Framework (DB-SAF).

The thesis filled research gaps as discussed as follows.

First gap (*Identify*): To identify ambiguity in architecting systems with a high degree of innovation and highly exploratory objectives.

How this thesis filled this gap: This thesis identified potential sources of ambiguity in systems architecting by means of ontological analysis, and developed a framework to mitigate and identify ambiguities. Furthermore, the validation case study described in Chapter 6 defined a novel validation protocol to assess the effectiveness of Delphi outside of its original areas of applications in policymaking and forecasting.

Second gap (*Characterize*): To characterize ambiguity as an adverse factor to effective systems architecting.

How this thesis filled this gap: This thesis provides a framework for management of ambiguities, called the descriptive Systems Architecting Management Framework, and describes a taxonomy for classification of reducible and irreducible ambiguities, as described in Chapter 3.

Third gap (*Mitigate*): Enable mitigation of reducible and irreducible ambiguities in the functional intent of a systems architecture.

How this thesis filled this gap: This thesis presented a framework for quantitative analysis the value delivery process (Crawley 2008) of a system, including the assessment of ambiguity in the definition of stakeholder needs and in the functional intent process. It presents and informs strategies for effective mitigation of multi-domain ambiguities in systems architecting.

Fourth gap (*Integrate*): To integrate ambiguity assessment through expert elicitation techniques with formal system architecting methods in conventional systems engineering practice.

How this thesis filled this gap: This gap is filled by integration of quantitative expert elicitation for requirements definition with traditional design space exploration models. The framework presented in the thesis allows the exploration of large design spaces through the integration of hybrid MDO approaches.

## 7.4. Opportunities for Future Work

The research developed in this thesis could be advanced by pursuing several avenues for future work in this area. A selection of opportunities of future work follows:

- **Application of this method to additional case studies in scientific and engineering fields, within and beyond aerospace engineering.**

The systems architecting framework proposed in this thesis has been applied to three case studies: Mars Sample Return, In-Orbit Transportation Infrastructure for human spaceflight missions beyond Low Earth Orbit, and a retrospective analysis of communications satellite constellations in Low Earth Orbit. Further applications of this framework could be identified in other areas of aerospace engineering and other disciplinary domains. The framework could be adapted for case studies in other science and engineering fields, as well as extended to quantitative studies in support of policy-making.

- **Extend the validation case study to a larger and international pool of subjects to study the effect of cultural differences in leadership, gender and age differences, and behavioral aspects of interest.**

The validation case study presented in Chapter 6 is a pilot case study to identify trends and patterns suggesting the improvement in system architecting outcomes when compared to conventional group-decision making processes when applied in this setting. As discussed in Section 6.8, one must be careful when extending the generalization of these results to a broader set of claims. Group decision-making is a complex process which is influenced by a myriad of exogenous factors, such as time, personal background, personality, culture, and so forth. The validation protocol developed in Chapter 6 could be extended to a larger set of subjects worldwide to study questions of interest in social science research and behavioral influences in decision-making. Questions of interest include: how do cultural differences and different leadership styles in different nations affect system architecting processes in joint international cooperation efforts? How do behavioral aspects and differences in gender and age affect decision-making processes as applied to systems architecting? Such broad claims will require a much larger pool of subjects, which will increase confidence on obtained results.

- **Development of further expert elicitation tools to represent subjective value judgements deriving from expert knowledge.**

Latest developments of utility theory such as utility copulas (Abbas 2010) can be used to represent utility switches in preference structure and other complex decision-making behaviors. Another area of particular interest is artificial intelligence and machine learning tools of supervised and unsupervised learning. These tools can be used to improve the effectiveness of exploration of large trade-spaces, and to identify hidden patterns in multivariate data analysis – both interesting features that could be applied effectively in systems architecting problems.

- **Integrate the framework for systems architecting under ambiguous stakeholder objectives with concurrent engineering processes for pre-phase A / phase A system design studies.**

The approach developed in this thesis is concerned with high-level systems architecting, as it focused on broad programmatic and system development decisions. With proper modifications, the approach could be used in systems design processes such as spacecraft design, with particular reference to applications in concurrent engineering environments. Concurrent engineering is a systems design methodology that is widely adopted in the aerospace community worldwide (Carter and Baker 1992; Bandecchi, Melton et al. 1999). Elicitation of expert knowledge through the proposed framework can be integrated with concurrent engineering processes for structured inclusion of stakeholder feedback in these environments.

- **Development of a hybrid approach to systems architeting under ambiguous stakeholder objectives.**

The main strength of the proposed systems architecting framework is to reduce peer pressure while identifying, characterizing and mitigating ambiguities through a structured, iterative and anonymous expert elicitation process and its integration with conventional system architecting tools. While anonymity is a main feature of the approach, it also implies an important limitation to address in future developments of this method. Anonymity and indirect expert interaction prevents a more efficient exchange of knowledge and opinions between experts that could be obtained with conventional group decision-making process. To mitigate this limitation, a hybrid approach could be developed, by having experts interact in "Round 0" iterations preliminary to the application of the Delphi-Based Systems Architecting Framework. Experts can gather at intermediate stages during DB-SAF rounds to update their positions and facilitate transfer of knowledge. While capturing this advantage of conventional group decision-making, this hybrid approach also allows to retain the advantages of anonimity as it allows unpressure exchange of knowledge through anonymous polls. The characterization of performance of this hybrid approach is an area of future work. The main limitation being foreseen is the need for availability of experts to gather at the same time – either in person or remotely – for direct interaction stages. This might prove being challenging (or unfeasible) for large expert groups and panels with senior experts and high-level decision-makers. On the other hand, this capability has been demonstrated by the proposed approach in this thesis, as the case studies benefited from inputs from senior scientists, engineers and aerospace managers.

- **Apply online software and active learning approaches to systems architecting under ambiguous objectives.**

A sophisticated implementation of the proposed systems architecting framework in a concurrent engineering environment can entail the development of an online software to automate the execution of the systems architecting framework and enable real-time interactions and real-time interview data processing with a large pool of interviewees distributed in multiple centers. The use of clickers as developed in active learning research (Hoffman and Goodwin 2006) is an additional tool to enable real-time application of the framework in the context of scientific workshops, engineering meetings, and concurrent engineering environments.

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# Chapter 9 : Appendices

## 9.1. Case Study 1 – HSF – Supplemental Material

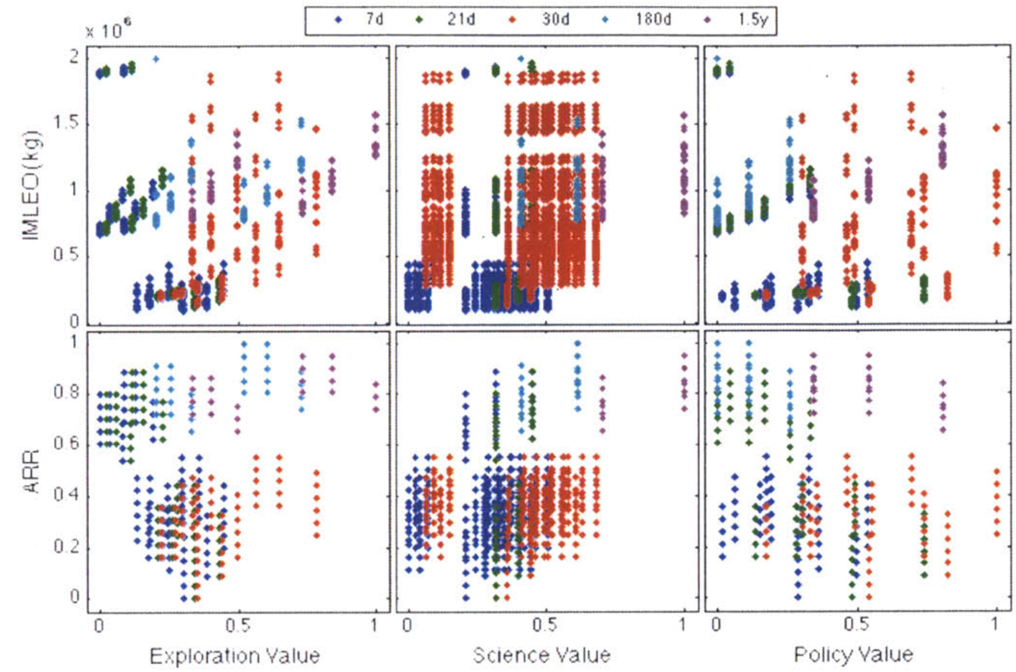


Figure 108 Architectural Design Space - Exploration Time View

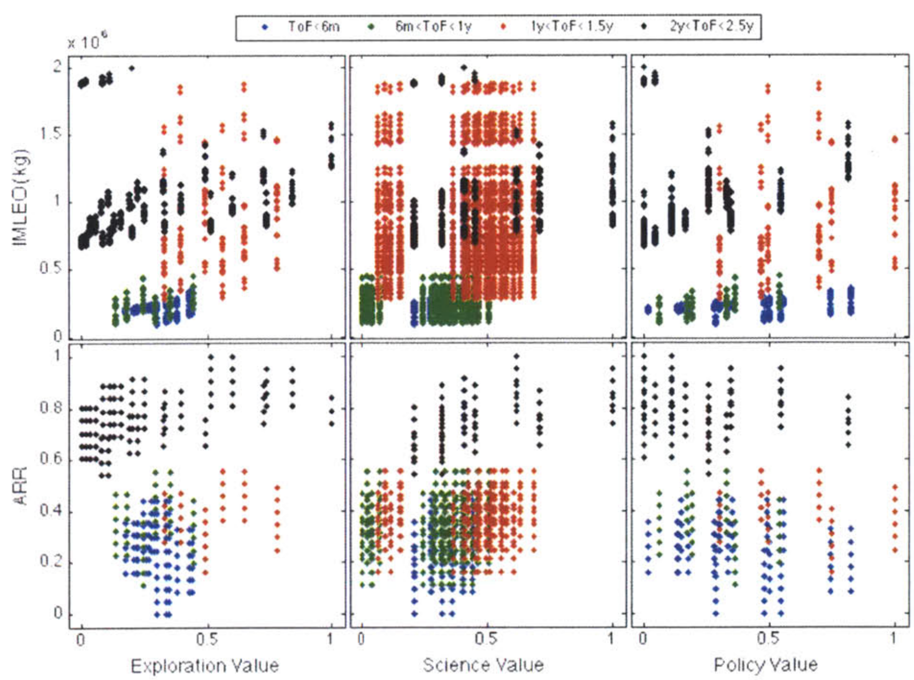


Figure 109 Architectural Design Space - Time of Flight View

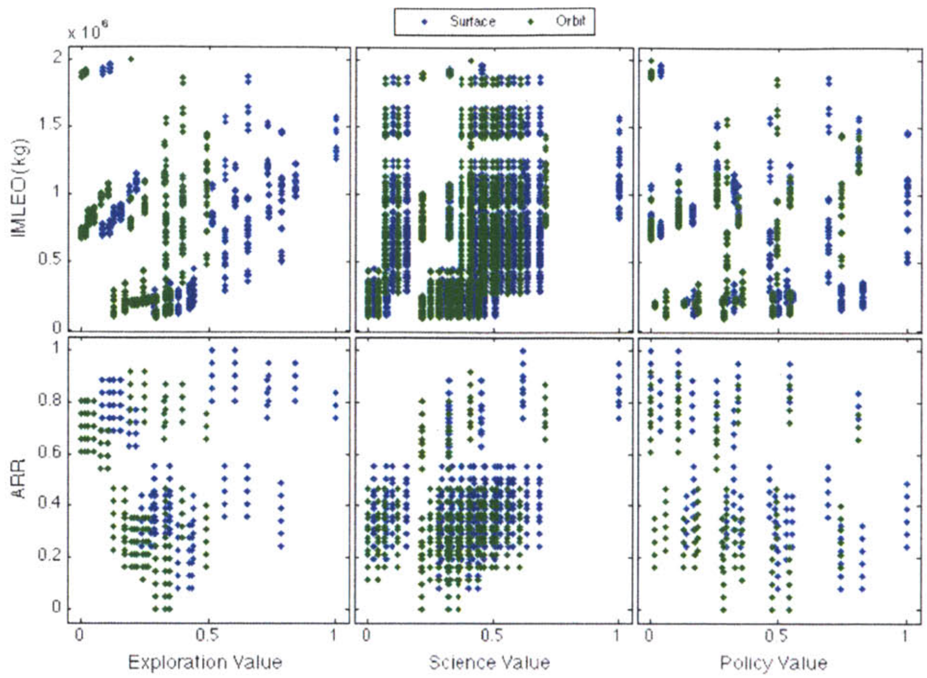


Figure 110 Architectural Design Space - Mission Mode View

| | Delta V required (km/s) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Departure from Earth | Arrival at Destination | Departure to Earth | Arrival at Earth | Descent to Destination | Ascent to Destination | Total |
| EML1 | 3100 | 700 | 700 | 3100 | 0 | 0 | 7600 |
| Mars Flyby | 3714 | 2115 | 2115 | 3500 | 0 | 0 | 11444 |
| Mars Orbit | 3714 | 2115 | 2115 | 3500 | 0 | 0 | 11444 |
| Mars Sortie | 3714 | 2115 | 2115 | 3500 | 2083 | 4000 | 17527 |
| Mars Long Stay | 3714 | 2115 | 2115 | 3500 | 2083 | 4000 | 17527 |
| Moon Flyby | 3600 | 850 | 850 | 3150 | 0 | 0 | 8450 |
| Moon Orbit | 3600 | 850 | 850 | 3150 | 0 | 0 | 8450 |
| Moon Sortie | 3600 | 850 | 850 | 3150 | 2083 | 1871 | 12404 |
| Moon Long Stay | 3600 | 850 | 850 | 3150 | 2083 | 1871 | 12404 |
| LoNEA Flyby | 3400 | 180 | 147 | 3200 | 0 | 0 | 6927 |
| LoNEA Orbit | 3400 | 180 | 147 | 3200 | 0 | 0 | 6927 |
| LoNEA Sortie | 3400 | 180 | 147 | 3200 | 2083 | 0 | 9010 |
| HiNEA Flyby | 4208 | 1359 | 1125 | 3200 | 0 | 0 | 9892 |
| HiNEA Orbit | 4208 | 1359 | 1125 | 3200 | 0 | 0 | 9892 |
| HiNEA Sortie | 4208 | 1359 | 1125 | 3200 | 2083 | 0 | 11975 |
| Phobos/Deimos | 4208 | 1359 | 1125 | 3200 | 2083 | 0 | 11975 |
| SEL2 | 3200 | 900 | 900 | 3200 | 0 | 0 | 8200 |

Figure 111 Delta V Assumptions for In-Space Transportation Architecting Model

## 9.2. Case Study 2 – MSR – Supplemental Material

### 9.2.1. Introduction

This appendix presents three preliminary design models that have been developed to enable architectural tradespace exploration in the Mars Sample Return Campaign case study. These are:

- A model for preliminary sizing of Entry, Descent and Landing (EDL) systems based on first principles;
- A parametric model for preliminary sizing of drilling payloads based on a data set obtained from a survey on existing drilling hardware for space applications;
- A first principle model for preliminary sizing of drilling payloads.

While the first and second model have been implemented in the architecting, the third model is presented "as is" as it was decided not to continue its further implementation due to lack of publicly available data on drilling payload specifications. On the other hand, the first two models have been validated with mass comparisons with existing hardware, showing appropriate accuracy for pre-phase A study applications.

### 9.2.2. Parametric Model for Preliminary Sizing of Entry, Descent and Landing Subsystems

A parametric model for preliminary sizing of EDL subsystems has been developed in the context of this work. The peculiarity of the model is that it does not require trajectory calculations to estimate the total integrated heating load (which is required for preliminary sizing of a heat shield). Instead, it proposes a linear correlation between the specific kinetic energy at entry conditions of the probe and total integrated heat load absorbed before landing. Table 40 and Table 41 show the data that has been used for development of the model. The model requires the following inputs:

- Heat Shield Diameter D [m]
- Drag coefficient $C_D$ [-]
- Entry mass $m_{entry}$ [kg]
- Entry velocity $v_{entry}$ [km/s]

Drag coefficient and entry velocity can be estimated by analogy with legacy Mars missions (Figure 113 and Table 40 respectively).

A MSL-like EDL subsystem Entry mass is conceptualized as the sum of landed mass, lander mass, mortar mass, parachute mass, ballast mass, backshell mass and heat shield mass (heat shield mass if further decomposed into structural mass and TPS mass). "Useful" landed mass is therefore estimated as:

$$m_{landed} = m_{entry} - m_{lander} - m_{mortar} - m_{chute} - m_{ballast} - m_{backshell} - m_{heatshield}$$

Figure 114 shows the linear correlation that has been found between specific spacecraft kinetic energy at entry and total integrated heating load:

$$E_{tot} = \left[1.6541\beta v_{entry}^2 - 1058.4\right](0.01)^2 \quad \left[J/cm^2\right]$$

Where $\beta = \frac{4m_{entry}}{\pi D^2 C_D}$ is the ballistic coefficient of the spacecraft at entry conditions in the Martian atmosphere.

The TPS mass fraction is obtained by a parametric relationship available in the literature (Laub 2003):

$$TPS\_MF = 0.091E_{tot}^{0.51575}$$

Therefore, TPS mass is estimated as:

$$m_{TPS} = TPS\_MF \cdot m_{entry}$$

The structural mass of the heat shield is estimated with a heat shield structural mass fraction available in the literature (Otero 2010):

$$m_{struct} = 0.08m_{entry}$$

Heat shield mass is the sum of TPS mass and heat shield structure mass:

$$m_{heatshield} = m_{struct} + m_{TPS}$$

Backshell mass is estimated with a parametric relation available in the literature (Otero 2010):

$$m_{backshell} = 6.7582m_{entry}^{0.4116}$$

Parachute mass and ballast mass are obtained with mass fractions estimated from the Mars Science Laboratory (MSL) rover:

$$m_{parachute} = 0.145m_{entry}$$

$m_{ballast} = 0.165 m_{entry}$

Likewise, lander mass is obtained with a mass fraction derived from MSL:

$$m_{lander} = \left(1 - \frac{775}{1541}\right) m_{entry} \cong 0.50 m_{entry}$$

Figure 112 shows a surface plot of the proposed EDL model of entry mass as a function of Aeroshell diameter and Useful Landed mass. It can be seen that the model is non-linear in both the x (aeroshell diameter) and y (useful landed mass) axes, with a strong non linearity corresponding to higher values for the aeroshell diameter.

This model properly represents the challenge of landing large masses on the Martian surface, and its validity for conceptual studies has been proven by validation with past flight missions. Table 42 and Figure 115 show the validation results against flown JPL missions, showing an accuracy <20% making the model suitable for preliminary sizing estimates.

Table 40 Data on EDL Systems of Past Flight Missions (1/2)

| | Viking 1 | Viking 2 | MPF | MER-A | MER-B | Phoenix | MSL |
|---|---|---|---|---|---|---|---|
| Entry Mass (kg) | 992 | 992 | 584 | 827 | 832 | 600 | 2800 |
| Ballistic Coefficient (kg/m^2) | 64 | 64 | 63 | 94 | 94 | 70 | 115 |
| Heat Shield Diameter (m) | 3.5 | 3.5 | 2.65 | 2.65 | 2.65 | 2.65 | 4.6 |
| Peak Heating Rate (W/cm^2) | 26 | 26 | 100 | 44 | 44 | 58 | 155 |
| | | | | | | | |
| Heat Shield TPS Thickness (in) | 0.54 | 0.54 | 0.75 | 0.62 | 0.62 | 0.55 | 0.9 |
| Entry Velocity (km/s) | 4.7 | 4.7 | 7.26 | 5.4 | 5.5 | 5.67 | 6 |
| Entry Flight Path Angle (deg) | -17 | -17 | -14.06 | -11.49 | -11.47 | -12.5 | -15.2 |
| Entry Flight Path Angle (rad) | -0.2967 | -0.2967 | -0.2454 | -0.2005 | -0.2002 | -0.2182 | -0.2653 |

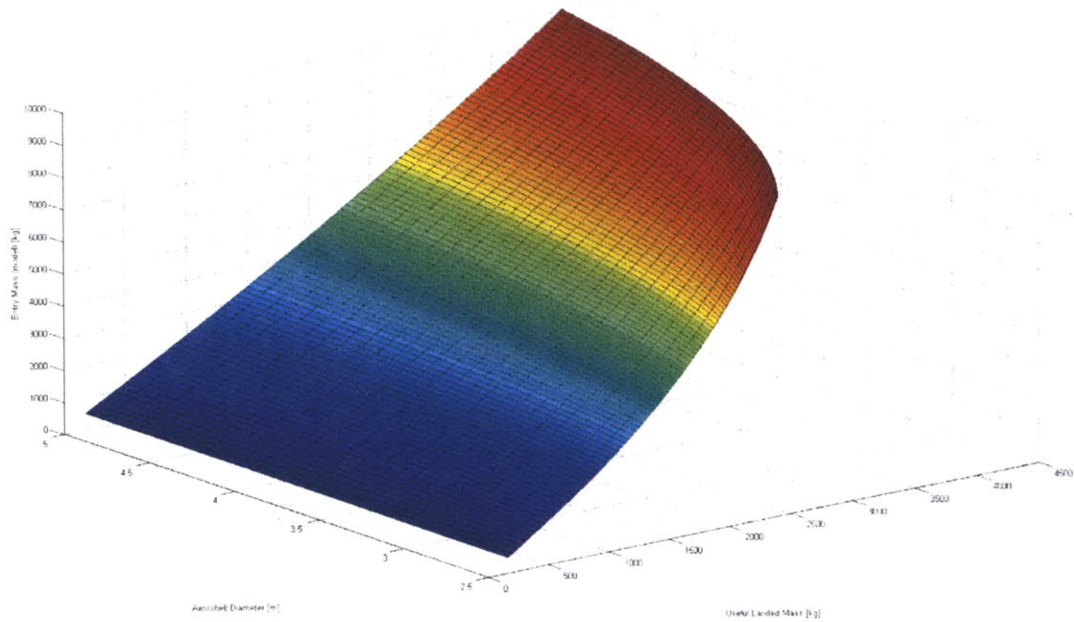

Figure 112 Surface plot of proposed EDL model

x-axis: Aeroshell Diameter (m)

y-axis: Useful Landed Mass (kg)

z-axis: Entry Mass (kg)

Table 41 Data on EDL Systems of Past Flight Missions (2/2)

| | Viking 1 | Viking 2 | MPF | MER-A | MER-B | Phoenix | MSL |
|---|---|---|---|---|---|---|---|
| Ball.Coeff. * v^2 | 1413.76 | 1413.76 | 3320.5788 | 2741.04 | 2843.5 | 2250.423 | 4140 |
| Total Integrated Heating (J/m^2) | 1100 | 1100 | 3865 | 3687 | 3687 | 3245 | 6000 |
| | 1100 | 1100 | 3865 | 3687 | | 2482 | 5455 |
| | | | | | | -23.5% | -9.1% |
| | | | | | | | |
| | Viking 1 | Viking 2 | MPF | MER-A | MER-B | Phoenix | MSL |
| Entry Mass (kg) | 992 | 992 | 584 | 827 | 832 | 600 | 2800 |
| Ballistic Coefficient (kg/m^2) | 64 | 64 | 63 | 94 | 94 | 70 | 115 |
| Heat Shield Diameter (m) | 3.5 | 3.5 | 2.65 | 2.65 | 2.65 | 2.65 | 4.6 |
| Heat Shield Reference Surface (m2) | 9.62 | 9.62 | 5.52 | 5.52 | 5.52 | 5.52 | 16.62 |
| Cd | 1.61 | 1.61 | 1.68 | 1.60 | 1.60 | 1.55 | 1.47 |
| Cd(average) | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 |

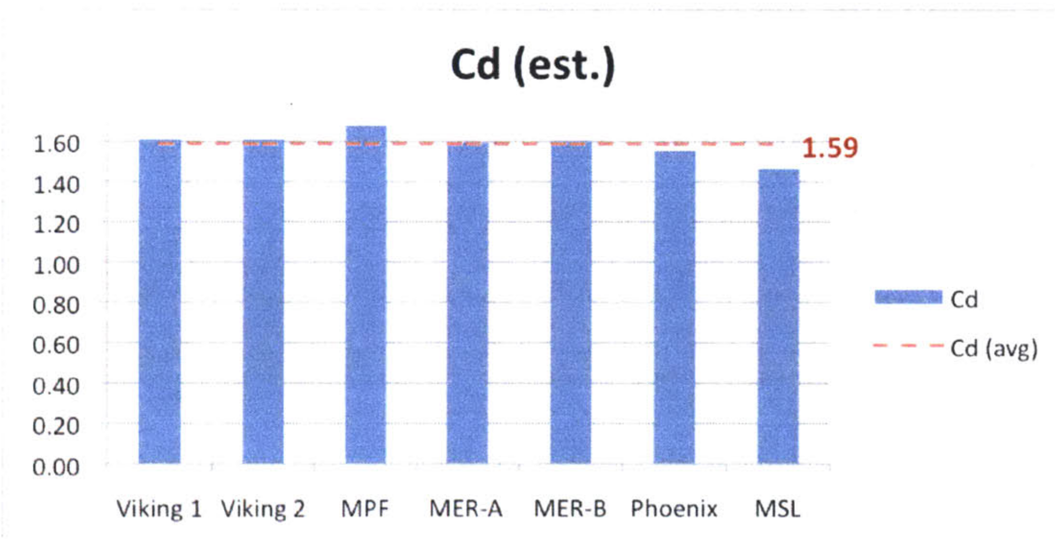


Figure 113 Drag Coefficient of Legacy Flight Missions

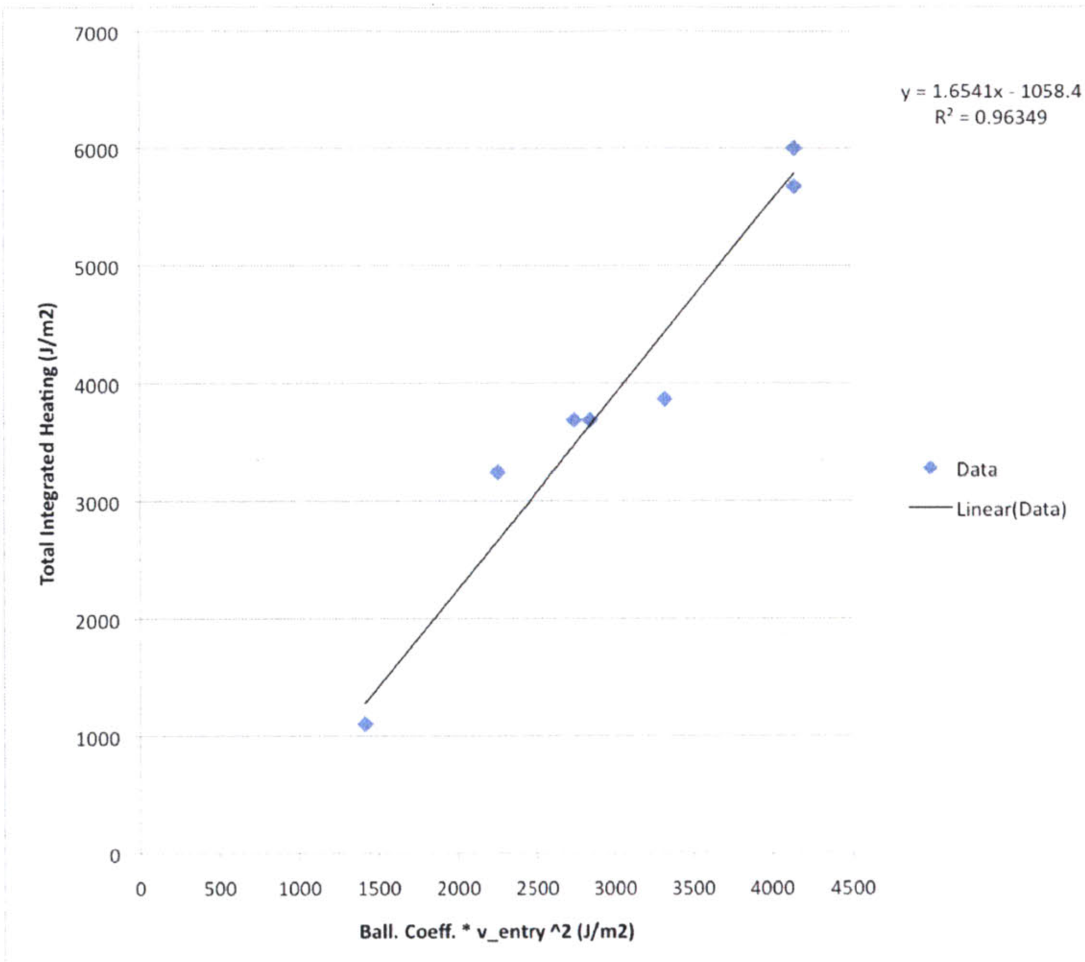


Figure 114 Linear correlation between total integrated heating and specific kinetic energy at entry

Table 42 Model Validation Data

| | Useful Landed Mass (actual) (kg) | Useful Landed Mass (est.) (kg) | Error on Useful Landed Mass |
|---|---|---|---|
| MSL | 896.8 | 775.0 | 15.7% |
| Viking | 221.5 | 244.0 | -9.2% |
| MPF | 107.9 | 92.0 | 17.3% |
| MER-A | 169.7 | 173.0 | -1.9% |
| MER-B | 170.3 | 173.0 | -1.6% |
| Phoenix | 165.6 | 167.0 | -0.9% |

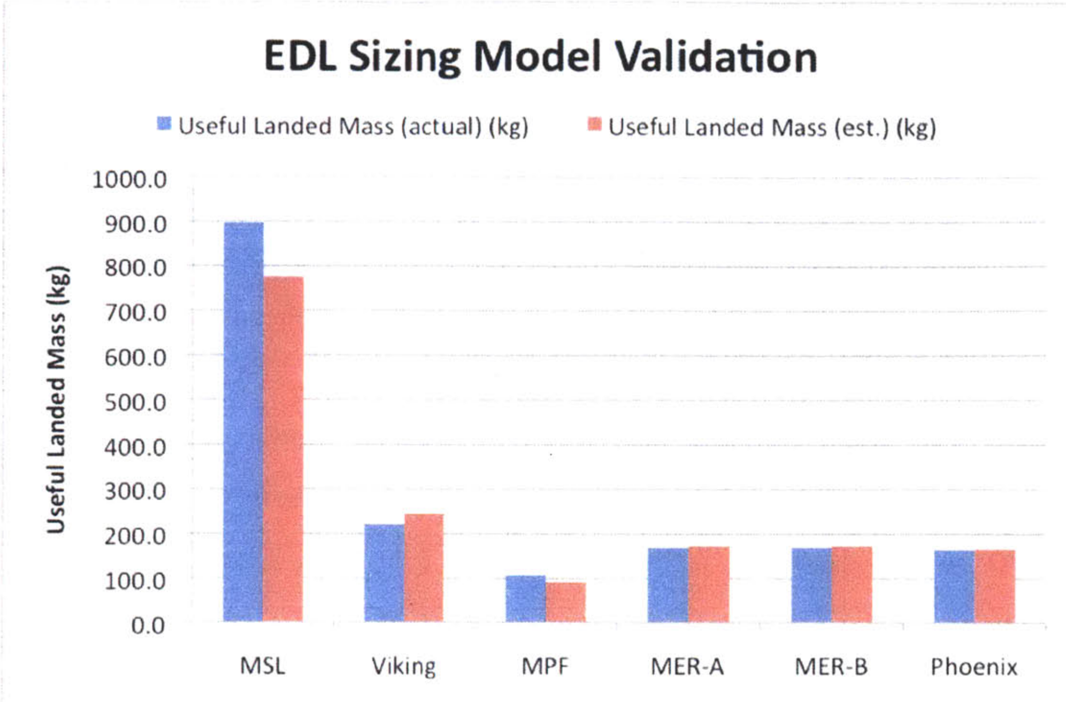


Figure 115 Model Validation with Past JPL Flight Missions

### 9.2.3. Parametric Model for Preliminary Sizing of Drilling Payloads

Figure 116, Figure 117 and Figure 118 show three proposed linear relationships for preliminary sizing of drilling payloads. The relationships are based on the dataset of existing drilling payloads shown in Table 43. The mass estimating relationships set a correlation between total drilling payload mass and maximum drilling depth. The 1mm-10m range has been divided in three sub-ranges to improve modeling accuracy. Validation of the model against available data points shows accuracy within 20%, rendering the model suitable for preliminary sizing studies. Inclusion of additional data points is encouraged to verify the applicability of the model to a broader set of studies.

Table 43 Drilling payload data used in parametric model development

| | Depth of penetration (mm) | Mass (kg) | Model Mass (kg) | Error (%) |
|---|---|---|---|---|
| MER RAT | 10 | 0.70 | 0.70 | 0% |
| Mini-Corer | 25 | 5.00 | 5.00 | 0% |
| CAT | 100 | 4.00 | 3.65 | -9% |
| Philae SD2 drill | 230 | 4.80 | 5.34 | 11% |
| Subsurface Sampler | 500 | 9.00 | 8.85 | -2% |
| HB 1-m drill / SATM | 1200 | 9.00 | 7.58 | -16% |
| Apollo drills | 3000 | 13.40 | 15.14 | 13% |
| SAHS (CanaDrill) | 10000 | 45.00 | 44.54 | -1% |

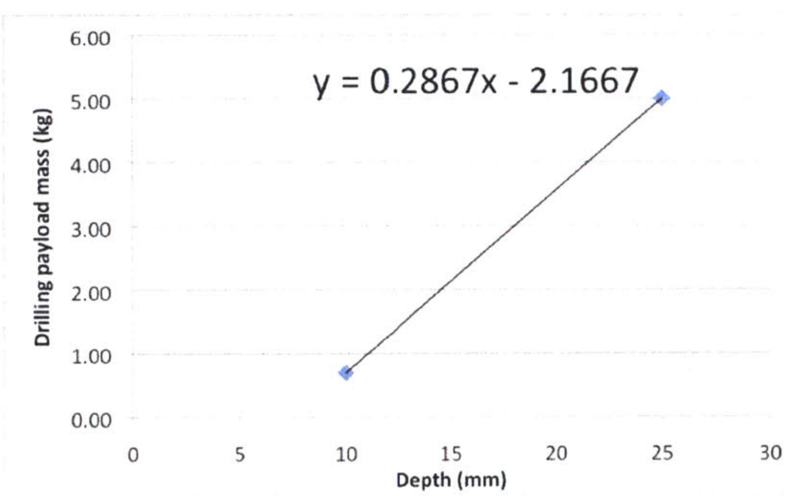


Figure 116 Parametric drilling payload sizing model, 0mm < depth < 30mm

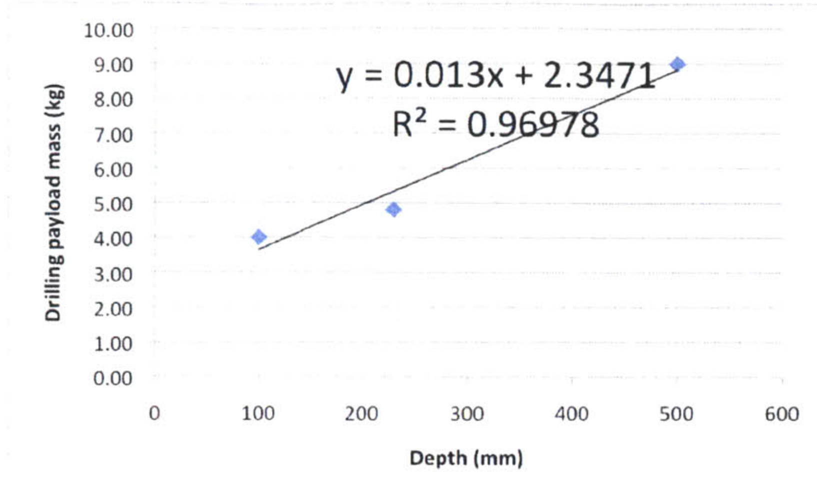


Figure 117 Parametric drilling payload sizing model, 100mm < depth < 500mm

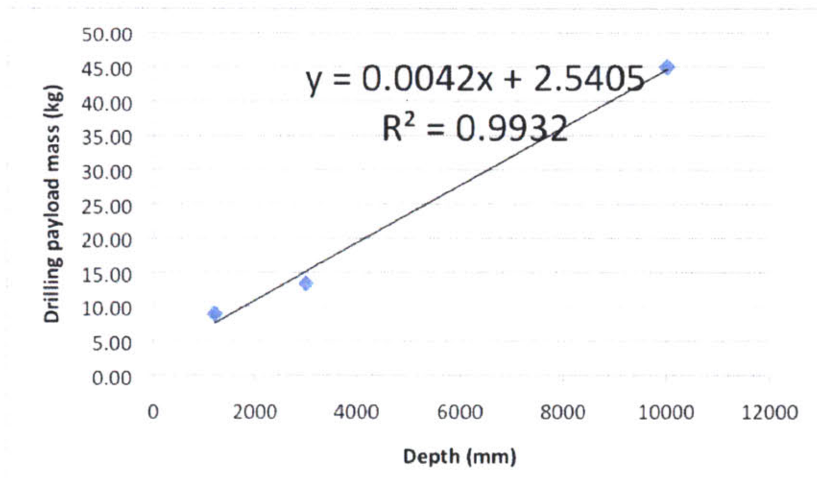


Figure 118 Parametric drilling payload sizing model, 1000mm < depth < 10000mm

### 9.2.4. First Principle Model for Preliminary Sizing of Drilling Payloads

This model performs a preliminary sizing of a drilling payload for planetary sampling based on fundamental physics and first principles. All units of measure are S.I. unless otherwise noted.

#### *9.2.4.1. Assumptions*

#### *9.2.4.2. Drilling Operations*

$T^*$= cumulative drilling time (total time available for drilling)

$\left[(k_0,d_0) \quad \ldots \quad (k_N,d_N)\right]$Sample quantity/depth distribution ( $k_0$ samples to be collected at depth $d_0$, etc.

Assume the RPM of the drilling bit (hence the RPM of the motor) is constant over the entire mission.

$\mu$= coefficient of sliding friction between the drilling bit and the rock surface. It is a function of both the drilling bit and rock surface material properties and drilling bit design. For preliminary design perform a worst-case assumption on this parameter (if desired, an sensitivity analysis can be performed)

#### *9.2.4.3. Electric Motor*

$$G = \frac{RPM(\text{motor})}{RPM(\text{drilling bit})} = \text{gear ratio between motor and drilling bit RPMs}$$

$$\eta_m = \frac{P_{BOL}(\text{consumed by drilling bit})}{P_{BOL}(\text{motor})}$$

#### *9.2.4.4. Drilling Bit Design*

The model assumes a full-faced drilling bit of known design. If desired, the model can be easily adapted to suit a core drill bit and trade different drill bit designs.

D = drilling bit diameter

$\delta$= depth of cut per drilling bit revolution (constant over time, i.e. no degradation is assumed on this parameter)

#### *9.2.4.5. Rock Properties*

SE = Specific Energy. In general, specific energy is a function of strength and abrasiveness of the formation to be drilled, of the drill bit design and aggressiveness of the drilling method. If drill bit is constant, SE can be approximated as a function of material properties only. If material is constant, SE can be approximated as a function of drill bit design only.

$\rho$= rock density

UCS = rock ultimate compressive strength

#### 9.2.4.6. Degradation of Rate of Penetration (ROP)

The Rate of Penetration decreases for a constant Weight on Bit (WOB), as the bit head flattens during drilling. This model assumes an exponential degradation of ROP as:

$$ROP_i = ROP_{i-1} e^{-\beta d_{i-1}}$$

Where $ROP_i$ is the Rate of Penetration at the i-th drilling operation, and $d_i$ is the depth drilled in the i-th drilling operation. $\beta$ is the degradation constant for the drilling bit, which can be estimated by least-square fitting of empirical data on the drilling bit design of interest.

#### 9.2.4.7. Model

The number of total required revolutions for the drilling bit for the mission equals:

$$\text{No\# of required revolutions} = \frac{\sum_{i=1}^{N} k_i d_i}{\delta}$$

The required RPM for the drilling bit is then:

$$RPM(\text{drilling bit}) = \frac{\text{No\# of required revolutions}}{T^*}$$

The RPM of the motor is obtained as:

$$RPM(\text{motor}) = G \cdot RPM(\text{drilling bit})$$

Assuming an exponential degradation model, the ROP at Begin of Life (BOL) can be estimated as:

$$ROP_{BOL} = \frac{Z}{T^*}$$

Where:

$$Z = \left\{ d_0 \left( 1 + \sum_{i=1}^{k_0 - 1} e^{\beta i d_0} \right) + \sum_{j=1}^{N} \left( d_j \sum_{i=1}^{k_j - 1} e^{\beta \left[ (k_0 - 1) d_0 + \sum_{l=1}^{k_i} d_l \right]} \right) \right\}$$

(this formula is obtained by iterating the exponential degradation model for ROP, calculating the time required for every single drilling operation by its associated ROP, and nesting the corresponding equations)

The Hole Area is calculated as a function of the drilling bit diameter (assuming a full faced drilling bit):

$$A = \frac{\pi}{4} D^2$$

The power consumed by the drilling bit at BOL is:

$$P_{BOL}(\text{consumed by drilling bit}) = SE \cdot ROP_{BOL} \cdot A$$

We can calculate the required Weight on Bit at BOL from the following equation (Zackny):

$$P_{BOL}(\text{consumed by drilling bit}) = \left( UCS \cdot A \cdot \delta + \mu \cdot WOB \cdot \overline{R} \right) \cdot \left( \frac{2\pi}{60} RPM(\text{drilling bit}) \right)$$

Where $\overline{R} = \frac{2}{3} R = \frac{D}{3}$ for a full-faced drilling bit.

The required motor power at BOL is estimated as:

$$P_{BOL}(motor) = \frac{P_{BOL}(\text{consumed by drilling bit})}{\eta_m}$$

The change in temperature at BOL on the drilling bit core is estimated as:

$$\Delta T_{core_{BOL}} = \frac{f P_{BOL}(\text{consumed by drilling bit})}{c_{rock} \rho_{rock} A \cdot ROP_{BOL}}$$

To avoid melting of the drilling bit core, a constraint must be satisfied such that:

$$Q_{core_{BOL}} = m_{core} c_{core} \Delta T_{core_{BOL}} < \text{heat of melting fusion of drilling bit}$$

## 9.3. Case Study 3 – Validation – Supplemental Material

**Email to Mailing List for Experts Recruitment**

Subject: Systems Architecting Role Play Experiment – FREE Lunch/Dinner and FREE $10 Amazon Gift Card to Participants

Dear Fellow Grad Students,

I would like to invite you to join me in a systems architecting "role play" experiment for my Ph.D. thesis. The experiment will last between 2 to 3 hours, and will be held between February 1-14 in the Aero/Astro Department. I will provide free lunch/dinner, refreshments and a free $10 Amazon Gift Card to all study participants.

This study is part of my thesis in Systems Architecting under Stakeholders Objective Ambiguity. You will be part of a steering committee to "make or break" the business case of a a new venture in aerospace planning to deliver a commercial point-to-point passenger transportation service.

You will either have a background in Engineering/Technology, Business, Policy or a combination of the three. No prior knowledge on suborbital flight systems required. SM and PhD candidates from Aero/Astro, ESD, Sloan, SDM and TPP are welcome to join.

Should you wish to participate, please email me at golkar@mit.edu and fill the following Doodle: http://www.doodle.com/qa3apmq5yk3eerb7 with your availability to participate on the different date options provided. In your email, please specify your background (indication of your course of study will do) along with your preference priorities on being involved in the Engineering/Technology, Business and Policy panels. I will follow up with more details and a final date/time decision once the Doodle fills up.

### More Details on the Business Case

DISCLAIMER: The Facts in this business case are fictional and for educational purposes only. The names of the parties, their businesses, and their trademarks and registrations are not intended, and should not be understood, to refer to or reference any individual living or dead or any institution, extant or defunct. Any resemblance to any real person, organization, product or situation is purely coincidental.

Suborbital Spacelines LLC is a new joint venture effort in the aerospace industry to deliver a commercial point-to-point passenger transportation service. Suborbital has conceived and designed a revolutionary concept for a spaceplane able to carry 100 passengers from London to New York in less than one hour.

Following several internal systems architecting studies and commissioning external consulting companies to conduct market surveys and market sizing estimates, Suborbital managers decided to form a steering committee to analyze the Company's business case and take a final decision to authorize the transition from detailed design to manufacturing spaceplanes and operating them. The steering committee includes three panels for Business, Technology and Policy matters. Each panel is staffed by junior and senior experts, in addition to panel leads. Suborbital's Chief Executive Officer will chair the panel and will hold the final decision on Suborbital's transition to manufacturing and operations.